RADIOLOGICAL DEFENSE

Vol. I


Hiroshima - 0815, 6 August 1945
Nagasaki - 1102, 9 August 1945
New Mexico - 0530,
16 July 1945
Bikini - 0835, 25 July 1946
Bikini - 0901, 1 July 1946

RADIOLOGICAL DEFENSE

A

Manual

Prepared by the

U.S. Joint Crossroads Committee

Vol. I

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FOREWORD

This manual, entitled "Radiological Defense," is a reprint of the same text formerly issued under the title of "Radiological Safety." The change of name conforms to the terminology recently adopted by the Armed Forces.

The original printing "Radiological Safety" was classified "Restricted." This volume of the manual has been reviewed and found to contain no restricted data under Public Law 585, 79th Congress, the Atomic Energy Act of 1946. The "Restricted" classification is, therefore, removed.

In order to save the expense of preparing new plates, the term "Radiological Safety" has not been removed from the interior pages of the text.

It is anticipated that Volume I will be followed by additional volumes which will be classified.

L. R. GROVES
Major General, USA

ERRATA

RADIOLOGICAL DEFENSE MANUAL, VOLUME I

The following is a list of corrections to the Radiological Defense Manual, Volume I (Radiological Safety Manual, Volume I).

Page No.	*Correction*
9	Equation (2) should read: $\frac{v-v_o}{t}$
13	In Equation (10) and the preceding equation, substitute G for k.
15	Commencing with the fourth paragraph of Section 2.07, through and including Equation (28) on page 16, substitute $\sqrt{z^2}$ for $\sqrt{x^2}$.
16	Second column, seventh line from bottom of page should read: $Nk=R$, the molar gas constant, =8.31 joules/
22	Equation (12) should read: $F=\frac{\pm m_1 m_2}{\mu r^2}$
23	Legend for figure 3—6 should read: The magnetic field at P will be due to the effect of all of the small segments $\triangle$s. With the current direction the field at P will be into the paper.
23	In Equations 13 and 14 change the alpha symbol to proportional sign $\propto$
29	First column, fourth and seventh lines: interchange symbols R and R_g
30	First column, third line should read: "The force on a charge e will then be:"
30	First column, second line from bottom, change e.s.u. to read e.m.u.
30	Table II, change first line under "*Work and energy*" to read: V (e.m.u.)$\times$Q (e.m.u.)=ergs.
37	Equation (4): In the second term of the right-hand side of equation, substitute v for Greek letter Nu.
75	In the nuclear reaction equation shown in first column, change the subscript of Ra to 88, and the subscript of Rn to 86.
75	Second column, change fourth line to read: $m_{(p+e)}=1.00813$ m.u. (Precisely, the mass of the proton alone equals 1.00758 m.u. In calculation of binding energy, the nucleus is regarded as that of an atom in electrical equilibrium, i. e., each proton is in the presence of its corresponding orbital electron, and the two act as one particle insofar as mass is concerned. In formulae following, for convenience, the symbol m_p should be understood to represent the sum of the precise masses of proton plus associated electron. This principle is further extended below in dealing with the protons mentioned in connection with an element ${}_2X^4$ which may be regarded either as α or as a helium atom depending upon degree of precise academic accuracy desired.)
76	Table III: BEPP (last column) of ${}_1H^2$ should read 1.09.
82	In Equation (23), place a minus sign ahead of subscript 1 to indicate negative *electron*, thus ${}_{-1}e^0$
85	Next to last line, second column, delete "(see fig. 6–6)."
86	Fourth line, first column, delete subscript to make E_D read E.

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INTRODUCTION

Chapter 1

INTRODUCTION

The dropping of an atomic bomb on Hiroshima on the 6th of August 1945 inaugurated a new era in warfare. With this one new development, new horizons of offensive warfare were opened. To date five atomic bombs have been detonated, two of these in actual military operations and three for experimental purposes. The devastating effects of this new weapon against both material and personnel were graphically demonstrated by the two bombs dropped over Japan, where at Hiroshima alone, 10 square miles were destroyed and more than 100,000 casualties resulted. Although the Japanese military situation was already well nigh hopeless at the time these two bombs were detonated, they undoubtedly were primarily responsible for bringing the war to a rapid conclusion and eliminated the necessity for extensive amphibious operations.

Despite the tremendous devastation which was wrought by these attacks on Japan, it appears likely, as a result of the tests carried out during the summer of 1946 at Bikini, that the atomic bomb has even greater potentialities for destruction. While the atomic bomb produces damage by blast and fire, its most characteristic feature is the release of nuclear radiations in the form of neutrons, alpha and beta particles, and gamma rays. In Japan both bombs were detonated at relatively high altitudes so that the radiological effects were almost at a minimum. Most of the radioactive products of these atomic bomb explosions, which account for the persistent radiological hazards, were carried to high altitudes and dispersed. Despite this, instantaneous nuclear or ionizing radiation was directly responsible for an important number of the casualties.

In test Baker at Bikini, however, it was shown that when a bomb is detonated some distance below the surface of the water, these radioactive products are not dispersed in the upper atmosphere but are to a large extent deposited on the surface around the point of detonation and for considerable distances down-wind. These materials would not only produce casualties amongst personnel throughout an area far greater than that affected by the detonations in Japan but would also make that area dangerous for reoccupation for a long time thereafter. In the future these insidious radioactive materials may be dispersed without the use of an atomic bomb. Certain problems would have to be solved, however, before such dispersal could be carried out effectively and without hazard to the user.

While the atomic bomb was designed and used primarily for its direct destruction effects, no weapon has ever had such potentially widespread and serious psychological aspects, nor has any weapon ever been used in war which has offered such rich opportunity for exploiting fear of the unseen and of the unknown. Indeed the psychological effects of the atomic bomb may constitute its most significant feature from the military standpoint. Not only will people undergoing attack be affected, but also both in time of war and in time of peace all people will be influenced by the fear of possible attack. It is probable that this will continue until such time as wars can effectively and certainly be prevented. In time of war the fear and panic which might be produced in connection with the threatened or the actual use of the atomic bomb against the larger cities and strategic centers might seriously jeopardize, if not actually neutralize, the military effectiveness of these centers.

In considering the characteristics of atomic bombs which are of military or political significance, it is important to recognize both the potentialities and limitations which attend its many terrorizing effects. While no weapon used in war has been fraught with such opportunity for exploiting the fear of the unknown, no weapon presents the same difficulties insofar as control of fear among our own people is concerned. The atomic bomb is thus a weapon possessing great disadvantages as well as advantages, negative as well as positive values.

Long range aircraft, pilotless planes, and, perhaps in the not too distant future, guided missiles make possible the effective employment of special weapons of mass effect. These would include the atomic, biological, and chemical weapons. They may be employed alone, in combination, or in

conjunction with other weapons, for a diversity of both tactical and strategical uses. Technological developments in missiles require that all three receive more considered attention than after World War I, and make it incumbent on military planners to be intelligently aware of their potentialities and limitations. This is particularly important in planning defensive measures and in the training of personnel to cope with those problems of atomic warfare which have given rise to a new and highly complicated military technology known as radiological safety operations.

The physiological effects are produced by the radioactivity in two different ways. First external radiation will produce effects similar to those produced by X-rays. Personnel will not only be exposed to an external radiation hazard from the rays emitted at the instant of detonation, but such a hazard also exists from the radiation given off by particles of radioactive material which might be present in a bomb cloud or on a contaminated surface. This type of hazard will usually produce observable effects within 30 days of exposure. Second, the radioactivity provides a serious internal hazard, since inhalation or ingestion of radioactive materials even in low concentrations will produce serious physiological effects. Open wounds or cuts would also provide a ready means of entrance of this dangerous material into the body. Internal radiation hazard may not produce observable effects for several years after exposure.

Because of the extent of the radiological hazard following the detonation of an atomic bomb, it becomes necessary to develop methods of reducing its effects to an absolute minimum. Many people will be killed regardless of what measures are taken, but there will undoubtedly be an even larger number of people who will be border-line cases and who might be saved. It has been estimated that 20,000 lives might have been saved at Hiroshima if adequate safety measures had been taken. The larger the area affected by a single attack and the greater the number of people involved, the larger will be the number of border-line cases, and the greater the value of adequate defensive measures. Good planning and training in advance might well mean the difference between being overwhelmed or being able to continue. Panic following an attack might increase the size of the disaster manyfold. To minimize the effects of radiological hazards upon personnel there has been developed a philosophy and a technique of radiological safety. It is a new and highly specialized field requiring personnel trained in various technical subjects, and qualified at different levels of proficiency within these subjects. To detect and measure these hazards, in order that the risks to personnel can be properly evaluated, is the primary task of radiological safety personnel. Efficient training and the development of reasonable operating methods offers the only method of minimizing both the physiological and psychological effects.

To plan, organize or train for radiological safety operations as one phase of atomic defense it is necessary that those responsible be familiar with certain technical information and scientific facts. There is a vast amount of information available on atomic energy, some relevant to the problems of atomic defense and some not. This information is scattered within a mass of reports from medical, scientific, and industrial laboratories including those of Manhattan Engineering District and in the reports of Operation CROSSROADS.

This manual has been prepared as a preliminary effort to provide in one place, and in an organized manner, source material for all groups which may become involved in one aspect or another of radiological defense, a field new to military science. It does not aim to be a textbook for specialists in any particular field but to provide a general background of the many scientific, medical, and operational aspects. For example, the medical officer could not expect to find all the medical information which he would need on radiation injury in the chapter on "Medical Aspects." This chapter is primarily designed to acquaint non-medical people with the nature of the hazards so that they will understand the problems and be able to discuss them intelligently with medical personnel.

Chapters 2 to 8 include a discussion of the basic nuclear physics concepts necessary for an understanding of the problems presented by atomic warfare. While it is recognized that little, if any, knowledge of nuclear physics is required in order to carry out successfully the routine operations involved in radiological safety, it is felt that such a background is vital for all people who will become involved in the planning of radiological

safety operations or who will be faced with the necessity of making decisions in the event of the outbreak of atomic warfare. Without such a background it would be impossible for an individual to tackle new or unforseen problems. Since radiological defense is still an untried field, problems and techniques can be expected to be changing constantly. Since instrumentation will be one of the most important aspects of radiological safety for all personnel in this field, the theoretical and practical side of both electronic and photometric equipment used for detecting nuclear radiations are described in some detail in chapter 9.

In chapter 10 the best estimates of the effects of an explosion of the present atomic bombs are included in order to provide a picture of the nature and magnitude of the present day problems. Chapters 11 and 12 are included in order to provide a background of oceanography and meteorology since these sciences are important in determining the movement of water-borne and air-borne contamination. Next, both the medical effects of different types of radiation exposure and some of the philosophy involved in safety operations are discussed. The latter is felt to be particularly important because of the complex nature of the safety problems presented by atomic warfare. Finally a part describing various radiological defense operations is included in order to provide a background for individuals who will have the responsibility for organizing such operations. This background can only serve as a starting point for such organization. Only at Bikini and thereafter have any large scale radiological safety operations been attempted, and these were of course carried out on a totally different basis from those which would be required during war time. Operation CROSSROADS was primarily a scientific test carried out in peacetime so that as a consequence no risk of any sort could be accepted. In war time, certain risks will be inevitable. Undoubtedly problems will arise which cannot be foreseen in advance. Far greater flexibility will be required to solve these problems, and therefore the background and training of those responsible for radiological safety will be even more important. The magnitude and seriousness of the problems presented by radiological warfare cannot be overemphasized.

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Part II

BASIC PHYSICS

Chapter 2

MOTION AND ENERGY

2.01 Introduction

It may seem unnecessary to include in a text on radiological safety a relatively large section devoted to classical and contemporary physics and so a few words of explanation may be in order.

In any explosion there is a rapid release of latent energy. This energy, released at the point of detonation, can be transmitted to produce damage at distant points through either the high speed motion of particles or through waves. These subjects have been the intimate concern of physics for many years, are quite well understood, and can be of considerable help in explaining detonation phenomena.

In an ordinary chemical explosion the energy is released in a single act by the rearrangement of molecular bonds. The reaction goes promptly to completion and there are no delayed phenomena.

In an atomic explosion, on the other hand, the energy is released by a nuclear rearrangement and matter is converted into energy in accordance with the relation developed by Einstein:

$$E=mc^2$$

Since c, the velocity of light, has a value of 30 billion cm/sec, it is evident that huge amounts of energy can be obtained from the annihilation of small amounts of matter. Furthermore, all of the energy is not released in the primary cataclysm; dangerous radiation will be emitted for many months after the explosion.

If the hazards associated with the release of nuclear energy are to be well understood and adequately controlled, it is necessary to understand the mechanisms producing the energy release. To obtain this understanding it is necessary to become familiar with a considerable amount of basic and contemporary physics.

Physics is essentially an exact science, and as such makes free use of all applicable mathematics. It is however a science in which mathematics is closely related and applied to physical concepts; in the present treatment the emphasis will be placed on the concepts involved, and mathematical expressions will be used only as tools to arrive at results not otherwise obtainable.

2.02 Mathematical Notation

Mathematical equations will be used throughout the text and indeed the expression

$$E=mc^2$$

already used is such an equation. It should be noted that the rearrangement of an equation is merely a matter of convenience, and adds nothing new. Thus

$$m=\frac{E}{c^2} \text{ and } c^2=\frac{E}{m}$$

are merely rearrangements of the original form.

In the equations of physics the symbols refer to physical quantities and since the = signs means a complete equality it is necessary that the two sides balance in kind or dimensions as well as in quantity. It would be absurd to suppose an equation correct if it stated that a distance of 20 feet were equal to a time of 20 seconds. Other less obvious errors in dimensions can easily occur, and it is well to frequently check equations to see that they are dimensionally correct. It can be shown that all physical quantities can be reduced to various combinations of mass, length, and time. In the energy equation above it can be seen that energy is dimensionally equal to a mass times a velocity squared, and since velocity is a length divided by time, energy is dimensionally

$$(E)=\frac{(ml^2)}{(t^2)}$$

The parentheses ( ) signify that the equation has only dimensional significance and that all purely numerical multipliers such as 1/2, 2π, or any other pure numbers have been omitted. Whenever energy is equated therefore, it must always be to a combination of factors which will reduce to ml^2/t^2.

It will soon be noticed that physics is concerned with numbers that are very large or very small as well as with those of more ordinary size. Thus the velocity of light is 30,000,000,000 cm. per sec. and the mass of an electron is

0.00000000000000000000000000009 grams

Obviously it is not convenient to work with num-

bers like these, and a change to larger or smaller units such as the kilometer or microgram does not solve the problem. It is possible to express these numbers as powers of 10 and this provides a compact and practical notation for handling both large and small numbers.

It is obvious from the definition of exponents that $10^2=100$, $10^3=1{,}000$ and so on. Thus 1,000 can be written as 1×10^3, 2,000 as 2×10^3 and so on. In this notation the velocity of light will be 3×10^{10} cm per sec. Similarly

$$0.01=\frac{1}{100}=\frac{1}{10^2}=10^{-2}$$

and hence the mass of the electron will be written 9×10^{-28} grams. The convenience of this notation can be seen when it is necessary to perform multiplications or divisions. $100\times1{,}000=100{,}000$ or in the exponential notation $10^2\times10^3=10^5$. Thus multiplication requires only the adding of exponents and division the subtracting. If it is desired to determine the energy liberated upon the annihilation of 2 micrograms of matter, the calculation is

$$\begin{aligned}E&=mc^2\\&=2\times10^{-6}\times3\times10^{10}\times3\times10^{10}\\&=18\times10^{14}\text{ or }1.8\times10^{15}\text{ ergs}\end{aligned}$$

The exponential notation is not confined to numbers which are integral powers of 10 but can be extended to include all numbers. Thus

$$3.162\times3.162=10$$

and since

$$10^{0.5}\times10^{0.5}=10^1=10$$

therefore

$$3.162=10^{0.5}$$

This scheme can obviously be extended so that corresponding to any number there will be an exponent to which 10 must be raised to equal the number. This exponent is known as the logarithm of the number to the base 10. In the usual notation then

$$\log_{10}100=2.000$$
$$\log_{10}1{,}000=3.000$$
$$\log_{10}3.162=0.500$$

It is not usually necessary to write the subscript 10, and the usual abbreviation for a logarithm to the base 10 is log. These logs are known as common logs. A little thought will show why, with our decimal system of counting, logarithms to the base 10 are so well suited for computations.

It is possible to develop a system of logarithms to any desired base, and one other base has turned out to be very useful. The base of this system of logarithms is 2.71828 . . . which is denoted by e. Logarithms to this base are known as Napierian or natural logarithms and are abbreviated *ln*. This number turns up quite frequently in theoretical calculations, and this is the reason the system of natural logarithms is important.

It is sometimes necessary to convert from one system of logarithms to the other. To find the relationship between them assume any number x such that

$$x=10^y$$

Then by definition $y=\log x$. Taking the natural logarithm of all the terms

$$ln\ x=y\ ln\ 10$$

But $ln\ e=1.000$, since e is the base of the system, and $ln\ 10=2.3$ . . . so finally

$$ln\ x=2.3\log x$$

and the multiplying factor 2.3 can be used to convert from common logs to natural logs.

2.03 Motion of Particles

In discussing the motion of a particle it might seem desirable to first define the word *particle*. Actually a simple rigorous definition is not possible. For many purposes the motions of small objects such as atoms (the smallest stable units of matter), molecules (stable aggregates of atoms) or electrons (the fundamental unit of electricity) can be satisfactorily described by considering them as mathematical points. In other cases the size and shape of these particles is all important. Similarly, bodies like the sun and the moon may frequently be studied by considering them as particles. Consequently the decision as to whether or not the motion of an extended body can be treated like the motion of a point must be decided in each individual case. When it is possible to use the relations developed for particles, the point considered is the center of gravity at which point

all of the matter of the body is supposed to be concentrated.

As a specific example, assume a particle which may be moving and assume that when we start to study this particle it is at the zero point of a coordinate system. We will arbitrarily measure time from the instant the particle was at the zero point. At some later time t the particle is found to be a distance s from the origin. The distance s is known as the displacement. It is obviously a quantity requiring both a magnitude and a direction for its complete specification. For example the chance of being hit by a bullet depends strongly on the direction in which the bullet is moving. Such directed quantities are called *vectors*, while quantities like time, which can be completely specified by a magnitude only, are known as *scalars*.

In studying motion a distinction is made between speed and velocity. Thus *speed* is a scalar quantity which gives the rate of displacement, or displacement per unit time, without regard to the direction of the displacement. *Velocity* is not only a measure of the rate of displacement, but is also a vector quantity, having the direction of the displacement. Velocity is a much more useful concept than speed.

Returning to a consideration of the moving particle, assume that the velocity is v_0 when $t=0$. At the later time t the velocity is v. If the acceleration is constant, then the average velocity over this interval is

$$\frac{v+v_0}{2}$$

and so the displacement, which is certainly equal to the product of the average velocity and the time being considered is

$$s=\frac{(v+v_0)}{2}\,t \qquad (1)$$

By analogy with velocity, which is the rate of displacement, *acceleration* can be defined as the rate at which velocity is changing. In symbolic form the acceleration a is

$$a=\frac{v-v_0}{t} \qquad (2)$$

since a is the change in velocity over time interval t. It should be noted that an acceleration has the dimensions of a distance divided by the square of the time and so is expressed as cm. per sec. per sec. which is frequently written cm/sec^2. Acceleration is a vector quantity having the direction of the vector difference $v-v_0$.

Equations (1) and (2) show the relationships existing between the five quantities s, v_0, v, t, and a. By algebraic manipulations two more equations connecting these quantities can be obtained. It should be pointed out that these new equations do not add anything fundamentally new, but are merely rearrangements which are more convenient for the solution of some problems. From Eq. (2)

$t=\frac{v-v_0}{a}$ and if this is substituted for t in Eq. (1)

$$2as=v^2-v_0^2 \qquad (3)$$

Solving Eq. (2) for v

$$v=at+v_0$$

Substituting this for v in Eq. (1)

$$s=\frac{(at+2v_0)}{2}\,t$$

or

$$s=v_0t+\tfrac{1}{2}\,at^2 \qquad (4)$$

If three of the five quantities are given any of the relations Eq. (1) to (4) can be used to solve for the other two.

If the displacements involved are along a straight line, the acceleration, a, can be determined by a simple algebraic subtraction. There is one very important case, however, where the displacement is not linear and where the calculation of a is more difficult. This is the case of motion at constant speed in a circle of constant radius. This situation is shown in figure 2–1.

When $t=0$, the particle is at A and has a velocity v_0 which has a direction perpendicular to the radius r. A short time t later the particle is at B, and the velocity v is equal in magnitude to v_0 but has a new direction. The factor $v-v_0$ needed to calculate a from Eq. (2) is obtained by a vector subtraction in the velocity triangle as shown. Now the velocity triangle is similar to the distance triangle OAB, since both are isosceles and the sides adjacent to the small angles are mutually per-

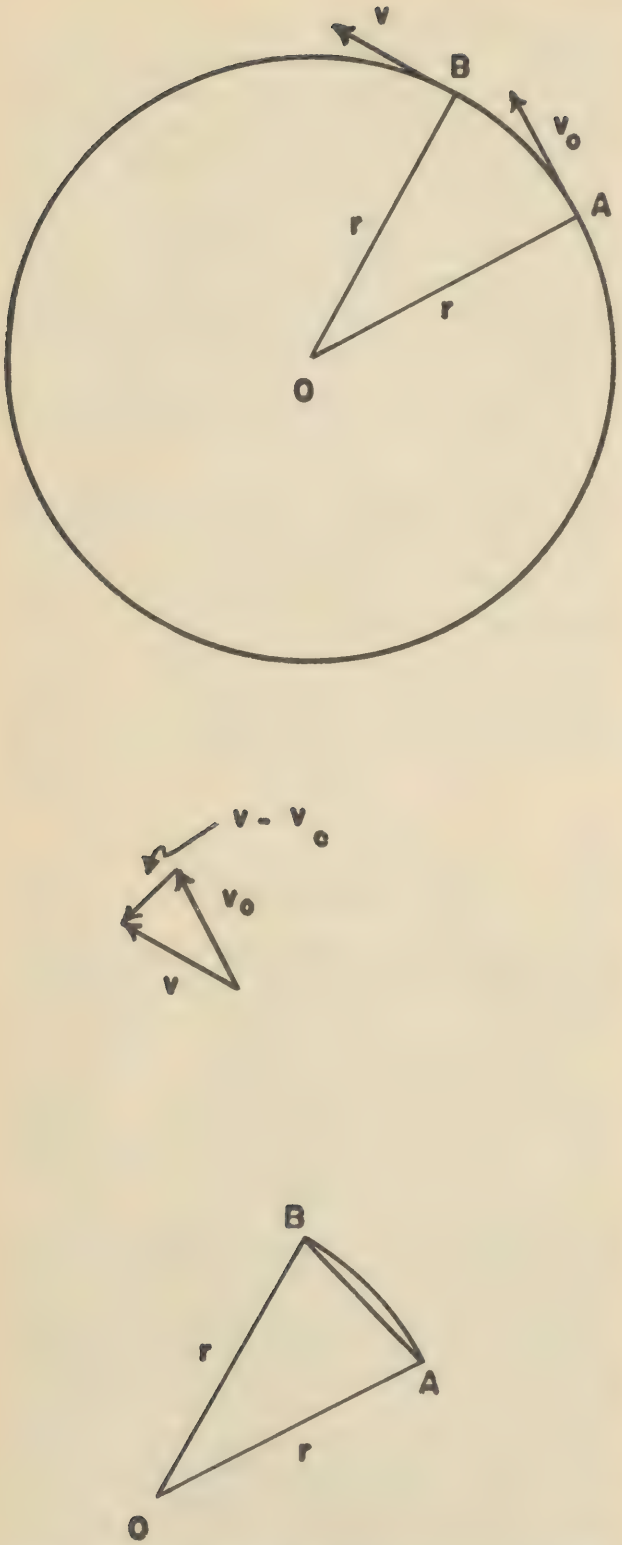

FIGURE 2–1.—The central acceleration of a body in uniform circular motion.

pendicular. Then corresponding sides are proportional and

$$\frac{v-v_0}{\text{chord } AB}=\frac{v}{r}$$

If the time t is made very small, the small acute angles become very small and chord AB becomes very nearly equal to arc AB. But arc $AB=vt$ hence

$$\frac{v-v_0}{vt}=\frac{v}{r}$$

and

$$a=\frac{v-v_0}{t}=\frac{v^2}{r} \qquad (5)$$

The acceleration has a magnitude of v^2/r and the direction of $(v-v_0)$, and this is toward the center of the circular path as can be seen from figure 2–1. As the particle proceeds around the circle, the magnitude of the acceleration remains constant; but the direction constantly changes, always remaining perpendicular to v. This is a very important relation which will be used later in the theory of atomic structure, the description of high voltage accelerators, and in other equally important applications.

2.04 Inertia, Mass and Force

A few simple experiments with bodies in motion are sufficient to show that an acceleration can only be brought about by some external influence on the body. Thus a body at rest remains at rest unless something is done to move it, and a moving body will continue to move until external actions bring it to rest. This tendency to maintain the status quo is known as *inertia*. The measure of inertia is known as *mass*, which is given the symbol m.

In the absence of any natural standard of mass it was necessary to set up arbitrary definitions and units. This has been done and carefully standardized kilograms are kept in various national laboratories. The gram, the unit of inertia in the metric system, has 1/1000 the inertia of a standard kilogram.

The influence which changes the state of motion of a body is called a *force*; it can probably be best defined in terms of Newton's first law of motion:

"A body at rest continues at rest and a body in motion continues in motion in a straight line with constant velocity unless acted on by a force."

A casual analysis of some motions may seem to indicate violations of this law, but more careful considerations will reveal elusive forces previously neglected. The most common force which changes motions is friction which appears in devious, insidious ways.

If a force acts on a body there will be a resultant acceleration. The quantitative relationship is given by Newton's second law of motion which states:

"If a resultant force acts on a body there will be an acceleration which will be proportional to the force and inversely proportional to the mass of the body."

Symbolically

$$a = k\,\frac{F}{m}$$

Where k is a constant of proportionality. The units of a and m have already been fixed (cm/sec^2 and gram respectively, in the metric system), and it would seem reasonable to define the unit of force so that the constant of proportionality is unity and can be neglected. The metric unit of force, the dyne, is then defined as that force which gives to one gram an acceleration of one cm/sec^2. With this definition, Newton's second law becomes

$$F = ma \qquad (6)$$

Some idea of the magnitude of the dyne can be obtained from a simple experiment. If any body is allowed to fall freely near the earth's surface, the gravitational attraction will impart to it an acceleration of approximately 980 cm/sec^2. This particular acceleration is encountered so frequently it is denoted by g. If specifically the experiment is performed with a mass of 1 gram, Eq. (6) shows that F must equal 980 dynes, and hence 1 dyne is about 1/980 of the earth's pull on a 1 gram mass. It cannot be said that a dyne is 1/980 of a gram. Such a statement is meaningless, for the dyne and gram are quite different quantities and can have no multiplicative relationship.

Newton's third law of motion is almost self-evident, and only a little reflection is needed to make it seem plausible:

"For every force there is a force of reaction equal in magnitude and opposite in direction."

An object placed on a table has acting on it the downward pull of gravity and indeed pushes downward on the table with a force equal to this gravitational pull. The reaction to this is the upward push of the table on the object. This must exactly equal the downward pull of gravity; otherwise the object would be accelerated in the direction of the greater force.

In writing Newton's second law in the form of Eq. (6) the tacit assumption was made that the mass of the body is a constant, independent of the state of motion of the body. This assumption seems a reasonable one and for nearly three hundred years laboratory experiments served only to confirm Newton's laws. It is true that Eq. (6) predicts that if a force is continually applied there will be a constant acceleration and hence velocity will increase without limit. Such a conclusion may be philosophically disturbing, but in the absence of definite experimental evidence Newton's laws were accepted as universally valid until the early years of the present century.

In 1905 Einstein published the first of a series of papers on the theory of relativity. Several of the conclusions drawn from this work were so revolutionary that they were not immediately accepted. Experiments soon verified many of the predictions, and at the present time there can be no doubt of the validity of the Einstein results.

One of the results was the equivalence of mass and energy, already mentioned. A second was that the mass of a body is not constant, but increases with velocity. It is necessary to recognize a rest mass, m_0 and a mass m corresponding to a velocity v. The relationship between these masses is

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} \qquad (7)$$

The factor v/c is the velocity of the body expressed as a fraction of the velocity of light and is frequently denoted by β (beta).

The term v^2/c^2 appears in Eq. (7) as a sort of correction factor which is obviously negligible at all ordinary velocities where v is very small compared to c. As v approaches c, the factor v^2/c^2 becomes increasingly important and indeed Eq. (7) predicts that if $v=c$ the mass m must become infinite. Hence if a body moves under the action of a force, its velocity cannot increase without limit. As the velocity approaches the velocity of light, the mass

increases in accordance with Eq. (7), and the actual velocity increase will be substantially less than that predicted from Eq. (6). A material body cannot be accelerated to a velocity greater than the velocity of light. This prediction has been amply confirmed by experiment. Particles with velocities within 0.01 percent of c have been measured; but no velocity greater than c has ever been observed.

It might seem from the above discussion that Newton's laws are of limited application; actually they hold with great accuracy from very low velocities to velocities of the order of 10^9 cm. per sec. They also hold for any type of acceleration, such as the central acceleration discussed in Sec. 2.03. The central force producing the acceleration is known as the centripetal force and the outward reaction to this is the centrifugal force.

In most of the applications which will be made, it will be sufficient to use the rest mass, but in a few cases the relativity corrections must be applied. Table I shows how the mass/rest mass ratio varies with v/c:

TABLE I

v/c	m/m_o	v/c	m/m_o
0.0	1.000	0.9	2.30
0.01	1.00005	0.95	3.16
0.1	1.005	0.99	7.10
0.5	1.159	0.999	22.3
0.7	1.402		

2.05 Energy and Potential

It is permissible to form combinations of the fundamental quantities previously described if it is useful or has a special physical significance. One such combination is the product of force and displacement, if we add the restriction that both must be measured in the same direction. This product, called *work*, seems a logical one, for common experiences in raising weights against gravity indicate that the accomplishment should be measured both by the force exerted and the height raised. In the metric system the unit of work will of course be the dyne-cm., and this unit is called the erg. For many applications the erg is an inconveniently small unit, and it is sometimes desirable to use the joule, which is equal to 10^7 ergs.

Since there is no time factor in the definition of work, and work done will be independent of the time required to make the displacement. In designing apparatus to do work, however, it is necessary to know the rate at which work is done. The rate at which work is done is known as *power*. The basic metric power unit, the erg per second, does not have a distinctive name but one joule per second is one watt, a unit of power frequently used in electrical calculations.

Reference has already been made to the gravitational attraction of the earth for a mass and it will now be profitable to examine this force more closely. It appears to act without any intervening medium for it is not changed when the attracted body is put in the highest obtainable vacuum. Other examples of similar forces will be described later, and no attempt will be made to explain the mechanism of the force transmissions.

It is important to recognize that the earth is surrounded by a region in which forces are exerted on masses. Such a region is known as a field of force, and in the particular case under discussion it is a gravitational field of force. The field strength, or field intensity, is the force exerted on a unit mass introduced at the point in question.

It can be shown that the earth's gravitational attraction is just a special case of the law of universal gravitation which states that all masses have a mutual attraction which is directly proportional to each of the masses, and inversely proportional to the square of the distance between them. It may also be shown that for all points outside of a mass it is possible to consider all of the mass to be concentrated at a mathematical point or center of gravity. Then for two masses, m_1 and m_2, whose centers are separated by a distance r:

$$F = G\frac{m_1 m_2}{r^2} \tag{8}$$

where G is the gravitational constant of proportionality. Since rather arbitrary units have already been chosen for m, r, and F, it is not probable that G will turn out to be unity. When m, r, and F are in grams, centimeters, and dynes, respectively, G has a value of 6.66×10^{-8}.

Although Eq. (8) shows that the gravitational force falls off rapidly with increasing distance, it is possible to consider F to be constant over a region where r is large and only small displacements are considered. Thus at the surface of the earth $r=5\times10^8$ cm and F may be considered constant up to an altitude of perhaps 10^6 cm. (33,000

feet). If then a body m originally at height a above some convenient reference point is raised to a height b the force required will be constant and equal to mg, and the work done will be

$$W=mg(b-a) \tag{9}$$

The work done in moving a unit mass from one point to another is known as the difference in the gravitational potentials of the two points. In the example cited, the difference in potential is $g(b-a)$ and the points may be said to have potentials of ga and gb, respectively.

The body under discussion can do work by falling back from b to a and since the ability of a body to do work is known as energy it has a greater potential energy at b than at a. From Eq. (9) and the definition of potential it is evident that the change in gravitational potential energy is m times the change in gravitational potential.

To consider the general case, assume a mass M and suppose points a and b to be so located that the force can not be considered constant. To calculate the potential difference m_2 in Eq. (8) is made unity. To make the calculation a small length Δr is considered over which F is essentially constant. The product $F \Delta r$ is calculated and added for all values between a and b. Such a process is known as integration. When this process is carried out we obtain,

$$V_b-V_a=km\left(\frac{1}{a}-\frac{1}{b}\right)$$

If the potential at infinity is arbitrarily set equal to zero the potential at any point r will be

$$V_r=-\frac{km}{r} \tag{10}$$

The minus sign indicates that as the mass is approached the potential becomes increasingly negative. This is correct because with attractive forces work will be done in approaching from infinity, and hence the potential must be lowered. A similar situation will be encountered when electric fields and potentials are discussed.

It is obvious that a body in motion has energy since it can do work, and so there must be an energy to be associated with velocity, just as potential energy is associated with position. This energy due to velocity is known as *kinetic energy*.

If a moving body has a force acting on it, it will be accelerated and the motion can be described by Eq. (3)

$$2as=v^2-v_0^2 \tag{11}$$

By Newton's second law of motion $a=F/m$ and using this in Eq. (11)

$$2\frac{Fs}{m}=v^2-v_0^2$$

or

$$Fs=\frac{1}{2}m(v^2-v_0^2) \tag{12}$$

The left side of Eq. (12) is obviously the work done on the body, and the right side is the increase in kinetic energy. Hence a moving mass has a kinetic energy

$$K.\,E.=\frac{1}{2}mv^2 \tag{13}$$

which will be in ergs if m is in grams and v is in cm per sec. It should be noted that kinetic energy has no direction and is not a vector quantity.

Energy can readily be transformed from one form to another, a common example being a falling body. As the body falls, potential energy is continuously converted into kinetic energy, which in turn is converted into other forms when the body is brought to rest. All energy exchanges are governed by the law of conservation of energy which states that "energy can be transformed but can not be created or destroyed." In any mechanical process, chemical or physical reaction there will be no loss or gain of total energy. With the discovery of radioactivity the law of energy conservation was seriously questioned, but the development of the Einstein mass-energy equation showed that the law must be retained with the extension that mass itself must be considered as one form of energy. In all chemical reactions the energy release is so small that the change in mass escapes detection. Only with the enormous energy releases from nuclear reactions can the mass changes be measured.

2.06 Momentum and Impulse

Although there is no doubt of the general validity of the law of conservation of energy, it is difficult to apply in many important cases because energy is easily transformed into elusive and hard-to-calculate forms. The collision of two automobiles is a case in point. There is no doubt

that total energy is conserved, but the amounts lost in heat, bending, and breaking are completely incalculable, and in such a process the energy principle is of no use in determining the final state of the system. Collisions are of great importance in atomic and nuclear physics and can be treated by considering momentum as well as energy.

Momentum is defined as the product of mass and velocity. It is a vector quantity having the direction of the velocity. Its importance lies in the fact that in any process whatsoever total momentum is conserved. To derive this principle consider two bodies with masses m_1 and m_2 and velocities v_1 and v_2 before a collision. After collision the velocities will be v_1' and v_2'. The motion of the first body can be described by Eq. (2)

$$a=\frac{v_1'-v_1}{t}$$

which by Newton's second law of motion becomes

$$\frac{F}{m_1}=\frac{v_1'-v_1}{t}$$

or

$$Ft=m_1v_1'-m_1v_1 \tag{14}$$

This could be used to calculate v_1' if F were known, but in a transient process, such as a collision, F is usually a complicated function which can not be used practically. By Newton's third law of motion the force on the second body will be $-F$ and hence a consideration of the second body yields

$$-Ft=m_2v_2'-m_2v_2 \tag{15}$$

The product Ft is known as *impulse*. The right hand sides of Eqs. (14) and (15) may be equated by changing signs. Then

$$m_1v_1'-m_1v_1=-m_2v_2'+m_2v_2$$

or

$$m_1v_1'+m_2v_2'=m_1v_1+m_2v_2 \tag{16}$$

This shows that the total momentum before collision is the same as the final total momentum. The momentum of the total system is conserved and nothing need be known of the forces involved.

As a simple example of the application of this principle, consider the ejection of an alpha particle from a radium nucleus (ch. 6, sec. 6.02). The alpha particle has a mass of about 6.7×10^{-24} grams and is ejected with an initial velocity of about 1.5×10^{9} cm/sec. The mass of the radium nucleus is about 371×10^{-24} grams so the recoil nucleus, after the ejection of the alpha particle, will have a mass of 364×10^{-24} grams. The radium atom is at rest before the ejection, so the initial momentum is zero; and from Eq. (16)

$$364\times10^{-24}v_1'+6.7\times10^{-24}\times1.5\times10^{9}=0$$

or

$$v_1'=-2.8\times10^{7} \text{ cm. per sec.}$$

The (−) sign indicates that the recoil velocity is opposite to that of the alpha particle. Kinetic energy has obviously not been conserved for initially it was zero and after the ejection was

K. E. (alpha particle)
$=\frac{1}{2}\times6.7\times10^{-24}\ (1.5\times10^{9})^2=7.5\times10^{-6}$ ergs

K. E. (recoil nucleus)
$=\frac{1}{2}\times364\times10^{-24}\ (2.8\times10^{7})^2=1.4\times10^{-7}$ ergs

Another process of considerable interest is the perfectly elastic collision where kinetic energy as well as momentum is conserved. (Ch. 9, sec. 9.12.) Consider a particle of mass m and initial velocity v_0 colliding with a stationary particle of mass M and imparting to it a velocity V. Since momentum is conserved

$$mv+MV=mv_0 \tag{17}$$

and if kinetic energy is also conserved

$$\frac{1}{2}mv^2+\frac{1}{2}MV^2=\frac{1}{2}mv_0^2 \tag{18}$$

To determine the energy transferred to the struck particle its final velocity V must be determined in terms of v_0. Rearranging Eqs. (17) and (18)

$$v=v_0-\frac{M}{m}V \tag{19}$$

$$v^2=v_0^2-\frac{M}{m}V^2 \tag{20}$$

Hence

$$V=\frac{2m}{m+M}v_0 \tag{21}$$

The kinetic energy received by the struck particle and hence that lost by the incident particle is

$$\text{K.E. transfer}=\frac{2m^2M}{(m+M)^2}v_0^2 \tag{22}$$

It can readily be shown that this will be a maximum when $M=m$, and so if it is desired to absorb energy through elastic collisions, the particles in the absorber should have the same mass as the incident particles.

2.07 Elementary kinetic theory

An immediate application of the principle of conservation of momentum is the kinetic theory of gases. In this theory, a gas enclosed in a container is considered to consist of a large number of molecules, each moving and hence having kinetic energy and momentum. The number of molecules is enormous, and it is impossible to calculate the behavior of each one. It is possible, however, to resort to an averaging process, and here the large number has the advantage that fluctuations from the average will be small.

Specifically, assume a rectangular container with dimensions *abc*, figure 2–2, coinciding with a set of coordinate axes *X*, *Y*, *Z*.

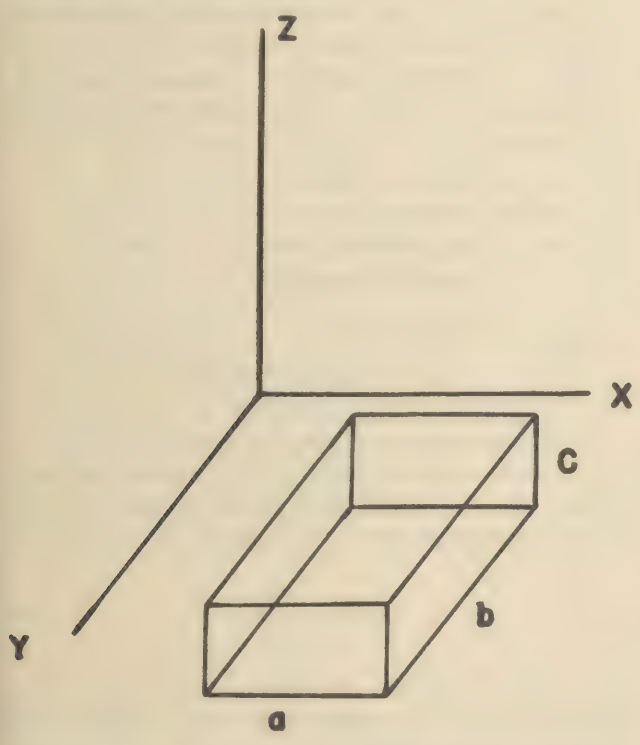

FIGURE 2–2.—Gas volume used for deriving the equation of the kinetic theory of gases.

Let the box contain n molecules each having a mass, μ. One molecule will have a velocity v and this will have components x, y, and z along the coordinate axes. From simple considerations of components:

$$v^2=x^2+y^2+z^2$$

$$v=\sqrt{x^2+y^2+z^2}$$

Average values will be denoted by $\overline{\ }$, as: $\bar{v}$. Obviously $\bar{v}$ is zero and the same holds for $\overline{x}$, $\overline{y}$, $\overline{z}$, If this were not so, there would be a movement of the gas in some preferred direction. If all the velocities are squared and then averaged, the mean square velocity $\overline{v^2}$ is obtained. This is not zero, since the squares of negative numbers are positive. There is still no preferred direction however, and:

$$\overline{x^2}=\overline{y^2}=\overline{z^2}=\frac{\overline{v^2}}{3} \tag{23}$$

The square root of a mean square velocity, $\sqrt{\overline{v^2}}$, is known as a root mean square velocity and this may be used in the calculations, assuming that each of the n molecules has this velocity with components $\sqrt{\overline{x^2}}$, $\sqrt{\overline{y^2}}$, $\sqrt{\overline{z^2}}$.

Consider the average molecule colliding with the face *ab* of the container. The velocity component perpendicular to the face is $\sqrt{\overline{x^2}}$. The molecule will make a perfectly elastic collision with the wall and will rebound with the same velocity in the opposite direction. Then by Eq. (14)

$$Ft=2\mu\sqrt{\overline{x^2}} \text{ per collision}$$

If the number of collisions per second is determined, t can be put equal to unity, and the total force on the wall calculated. Before the molecule can again collide with *ab*, it must travel a distance $2c$ which it does with an average velocity $\sqrt{\overline{x^2}}$. Then the time between collisions is:

$$\frac{2c}{\sqrt{\overline{x^2}}}$$

and the number of collisions per second with *ab* will be:

$$\frac{\sqrt{\overline{x^2}}}{2c}$$

Since there are n molecules, the total collisions per second will be n times this and:

$$F=\frac{n\mu}{c}\overline{x^2} \tag{24}$$

Since the total force is equal to the pressure p times the area ab:

$$pab=\frac{n\mu}{c}\overline{x^2}$$

or

$$pV=n\mu\overline{x^2} \tag{25}$$

$$=\frac{n\mu\overline{v^2}}{3} \tag{26}$$

The right hand side of Eq. (26) is 2/3 the total kinetic energy of the molecules. The left side is in the form of the law for perfect gases discovered empirically by Boyle and Gay-Lussac:

$$pV=nkT \tag{27}$$

Where k is Boltzmann's constant and T is the absolute temperature. Zero on the absolute scale is $-273°$ C. Comparing Eq. (25) and (27):

$$\frac{1}{2}kT=\frac{\mu}{2}\overline{x^2} \tag{28}$$

Where $\frac{1}{2}$ is written into each side to emphasize the close relation between T and kinetic energy. In terms of $\overline{v^2}$:

$$\frac{3}{2}kT=\frac{\mu}{2}\overline{v^2} \tag{29}$$

Eqs. (28) and (29) show that when the temperature of a gas is raised the energy required goes into increasing the molecular kinetic energy. Eq. (29) also points out that the kinetic energy of a molecule is zero at absolute zero. The factor 3 in Eq. (29) appears because the molecules considered can absorb energy in only three ways (x, y, and z velocities), and hence are said to have 3 degrees of freedom. In a diatomic molecule, which behaves much like a dumbbell, energy can, in addition, be absorbed by two modes of rotation, and in this case a 5 would be required in the equation comparable to Eq. (29). Similarly, a triatomic molecule has 3 modes of rotation and a total of 6 degrees of freedom.

The temperature-energy equation (Eq. 29) is valid for a single molecule; for future applications it is more desirable to change to a molar basis. This can be done with the aid of a few observations in simple chemistry.

It has long been known that the weights of elements which combine to form compounds always bear a constant ratio. Thus 1 gram of hydrogen always combines with 8 grams of oxygen to form 9 grams of water. By studying a large number of such reactions it has been possible to assign to each element a number proportional to its combining weight. Thus oxygen is given an atomic weight of 16 and forms the basis of the system; hydrogen then has an atomic weight of 1.008, chlorine 35.457, etc. These numbers do not have units, such as grams; they are merely relative. However, 1.008 grams of hydrogen will exactly combine with 35.457 grams of chlorine to form 36.465 grams of hydrogen chloride. This and other similar evidence suggests that there are the same number of atoms in 1.008 grams of hydrogen and 35.457 grams of chlorine, and that these combine one to one to form hydrogen chloride. The quantity of any substance having a mass in grams numerically equal to its atomic weight is known as one *gram-atom*, or one *mole*.

The number of atoms in a gram-atom is known as *Avogadro's number*. It has been measured in a number of ways, the present accepted value being 6.1×10^{23}. Although gases were used in the discussion, Avogadro's number applies to all elements or compounds. Thus there will be 6.1×10^{23} atoms in:

16 grams of oxygen
107.88 grams of silver
200.6 grams of mercury
238.14 grams of uranium

and 6.1×10^{23} molecules in:

18.016 grams of water (H_2O)
32.00 grams of oxygen (O_2)
36.465 grams of hydrogen chloride (HCl)

It is now evident that Eq. (29) can be put on a molar basis by multiplying both sides by Avogadro's number, N:

$$\frac{3}{2}NkT=\frac{N\mu}{2}\overline{v^2} \tag{30}$$

$Nk=R$, the molar gas constant, = 8.31 ergs/degree/mole. The right-hand side is the total molar kinetic energy.

The energy required to raise the temperature of one gram of a substance one degree is known as the *specific heat*. For many purposes the specific heat on a per mole basis (C_v) is used instead

of on a per gram basis. Then for a gas by Eq. (30):

$$C_v = \left(\frac{N\mu}{2}\overline{v^2}\right)_{T+1} - \left(\frac{N\mu}{2}\overline{v^2}\right)_T$$

$$= \frac{3}{2}R(T+1) - \frac{3}{2}RT = \frac{3}{2}R \qquad (31)$$

This indicates that the molar specific heat of any monatomic gas is 12.2 joules or about 3 calories. For polyatomic gases these figures would be increased according to the number of degrees of freedom. It should be pointed out that Eq. (31) was obtained on the assumption that the gas was held at constant volume during the heating. If it is allowed to expand, more energy will be required, but that is a complication of no immediate importance.

Very substantial difficulties are encountered when the specific heat calculations are extended to solids. It has long been known from experiment that many metals obey the law of Dulong and Petit and have a specific heat of about 6 calories per mole. It is known from the phenomena of electrical and thermal conduction that in a metal there must be about 1 free electron per atom. These then constitute a sort of electron gas which might be expected to contribute to the specific heat. Recent calculations show that this electron gas is of such a nature that it does not contribute to the specific heat, and hence the law of Dulong and Petit can be explained by neglecting the electronic contribution.

The free electrons are of the greatest importance in explaining thermal and electrical conductivities. They are indeed responsible for both phenomena, and this explains the previously empirical fact known as the Wiedemann-Franz law that

$$\frac{\textit{electrical conductivity}}{\textit{thermal conductivity}} = \frac{\textit{Constant}}{T}$$

In picking materials for protection against flash burns, it is obvious that thermal conductivity and specific heat are important factors. With a low thermal conductivity high surface temperatures can be expected and fires may break out. With a high conductivity and specific heat, the energy of the flash may be spread through a volume of material, and a high surface temperature avoided.

Before leaving the kinetic theory, one remark should be made about the derivation of Eq. (25). In this derivation it was assumed that the molecules did not collide with each other and transferred momentum only to the walls of the container. Actually this is far from true and each molecule suffers many collisions with other molecules. If this were not so, the thermal conductivity of a gas would be equal to the average molecular velocity, which is of the order of several hundred meters per second.

It can be shown that the treatment given above is not altered when inter-molecular collisions are considered. For some purposes, such as a study of the electrical conductivity of gases, these collisions are of great importance, and to study them the concept of *mean free path* is introduced. This is the average distance travelled by a molecule between collisions. This certainly depends in a complicated way on the size and shape of the molecules and a complete treatment cannot be given here. The mean free path would be expected to be inversely proportional to the number of molecules present per unit volume and hence, from Eq. (26), to the pressure at constant temperature. This is the important fact for present purposes. At 1 atmosphere pressure, the mean free path is about 10^{-5} cm. At a pressure of 10 cm. of mercury, this has increased to about 10^{-4} cm

Chapter 3

ELECTRICITY AND MAGNETISM

3.01 Electrostatics

Electrical and magnetic phenomena have been recognized for centuries, and electricity has become one of the greatest servants of man, yet the fundamental nature of it remains obscure. Many of its properties are known, and its behavior can be accurately calculated. Two kinds of electricity, positive and negative, are recognized, and most matter appears electrically neutral because it contains equal quantities of the two kinds. Only when there has been a separation does the electrical make-up of matter become manifest. Electric and magnetic phenomena are intimately related to the release of nuclear energy. This chapter is devoted to a discussion of those aspects pertinent to the main subject.

The earliest method of charge separation was rubbing or close contact. If a hard rubber rod is rubbed with a cat's fur and the two separated, each will show electrification. In particular sparks will jump from them, and they will attract light objects such as bits of paper. If two rubber rods are electrified or charged and then brought together, a force of mutual repulsion will be observed. Since the same thing must have happened to each rod, it is evident that like charges repel. Similarly the two cat's furs will be found to mutually repel. When the rubber rod is brought near the cat's fur, however, a force of attraction is observed, and this leads to the law that like charges repel each other and unlike charges attract.

When careful measurements are made, it is found that an inverse square law is obeyed, and Coulomb's law states that the force between two charges, q_1 and q_2 separated by a distance r is

$$F = \pm \frac{q_1 q_2}{K r^2} \qquad (1)$$

The $\pm$ sign indicates that the force may be a repulsion or attraction depending on the polarities of q_1 and q_2. k is the specific inductive capacitance or dielectric constant of the medium between the charges. For empty space $k=1$, and it may be taken as unity for air in most calculations. For present purposes, k is considered to be strictly 1.0.

It will be noted that Coulomb's law has the same form as the law of universal gravitation,

$$F = G \frac{m_1 m_2}{r^2} \qquad (2)$$

except for a constant multiplier G. The units of F (dynes) and r (cm.) are established, and it seems reasonable to define the unit of charge, or quantity of electricity, so that the need for a constant is eliminated. The unit charge is then that charge which is repelled with a force of one dyne by an equal charge at a distance of one cm. in a vacuum. The unit of charge so defined is the statcoulomb, or electrostatic unit of charge (e. s. u.), and forms the basis for a system of units known as the electrostatic system.

There are many analogies between electric and gravitational forces. Consider, for example, a charge q placed on a hollow sphere of metal. Since the sphere is a conductor, the electricity is free to move about and will distribute itself uniformly over the surface because of the mutual repulsion of the like charges. Any charge brought near the sphere will experience a force given by Eq. (1), and hence there is an electric field around the sphere. As in the gravitational case, the entire charge may be considered to be located at the center of the sphere; then the field strength at any point outside the sphere will be

$$E = \frac{q}{r^2} \qquad (3)$$

where r is the distance from the point to the center of the sphere, since this E is the force exerted on a unit test charge brought into the field. The direction of the field will be the direction of the force on a positive charge.

It can be shown that the field strength inside the sphere is zero. To make this plausible, consider a charged sphere, shown in figure 3–1, with a unit test charge at the center. Each small portion of the sphere will exert a force on the test charge, and geometrically opposite portions will exert equal but oppositely directed forces. These will

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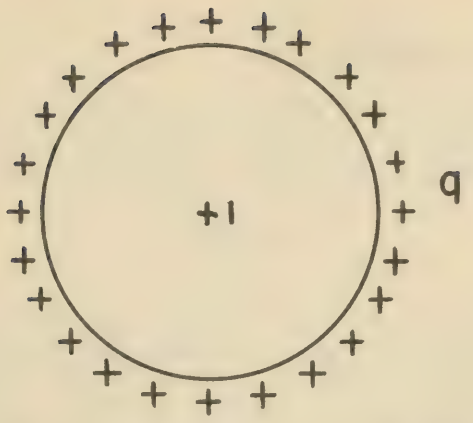

FIGURE 3–1.—A charge placed on a hollow conducting sphere distributes uniformly and exerts no force on a charge in the interior.

cancel, and hence there will be no net force and no electric field. This can be shown to be true for any point inside the sphere. This fact is used in the electrical shielding of sensitive instruments. A metal shield placed around the instrument will provide a field-free region unaffected by charges or fields outside the shield.

As in the gravitational case, electric potential difference between two points in a field is defined as the work done in taking a unit positive charge from one point to another. This is an important concept that will be used repeatedly throughout this text. It should be particularly noted that electrical potential is not analogous to water pressure, in spite of the popularity of the idea.

Consider a charge $+q$ located at 0, figure 3–2.

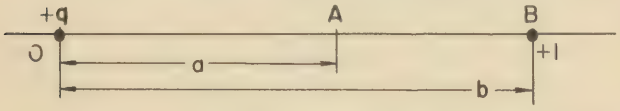

FIGURE 3–2.—Calculation of electrical potential at points A and B due to charge q by determining the work done in moving a unit charge.

It is desired to calculate the potential difference between points A and B in the field. The total work in moving the charge from B to A, and hence the potential difference, may be calculated to be

$$V_b - V_a = \frac{q}{b} - \frac{q}{a} \tag{4}$$

where V_b and V_a are the potentials at points B and A. The choice of a zero of potential is arbitrary, but a reasonable one would be to set the potential at infinity (V_∞) equal to zero. If this is done (4) becomes:

$$V_a = \frac{q}{a} \tag{5}$$

Eq. (5) shows that with like charges at 0 and A the potential becomes increasingly positive as a decreases. With unlike charges, the potential will also be given by Eq. (5), but must be negative. Since the force used in deriving Eq. (5) was in dynes and the distances were in centimeters, the potential V in the electrostatic system will be in ergs per statcoulomb. This is called the statvolt or the e.s.u. of potential. The work done in moving any charge through a potential difference will be equal to the product of the charge and the potential difference, and will be in ergs if both electrical quantities are expressed in e. s. u.

A very important component of electrical circuits consists of two conductors or plates, with

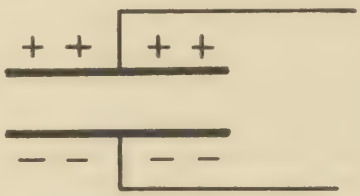

FIGURE 3–3.—Two insulated conductors form a condenser. The plates will have equal charges of opposite sign.

equal charges of opposite sign separated by a nonconductor or dielectric. The ratio of the charge on one plate to the potential difference between the plates is the capacitance, C:

$$C = \frac{q}{V} \tag{6}$$

where V is understood to be the difference in the potentials. In simple cases C can be calculated from the geometry of the system.

Consider an isolated metal sphere of radius a having a charge q. In this case the other plate is assumed to be at an infinitely large distance. From Eq. (5), the potential of the sphere is

$$V = \frac{q}{a}$$

and hence

$$C = \frac{q}{V} = \frac{q}{q/a} = a \tag{7}$$

Thus the capacitance of an isolated sphere is equal to its radius and the e. s. u. of capacitance is the centimeter. In the so-called practical system of electrical units, based on the volt and ampere, the unit of capacitance is the farad, a more familiar unit than the centimeter. To fix the size of the centimeter, it is worth remembering that, within 10 percent, one centimeter $=10^{-12}$ farad or one micro-micro-farad.

To consider a condenser more nearly like the definition, imagine a second sphere of radius b concentric with the first sphere and having a charge $-q$. See figure 3–4. This sphere does

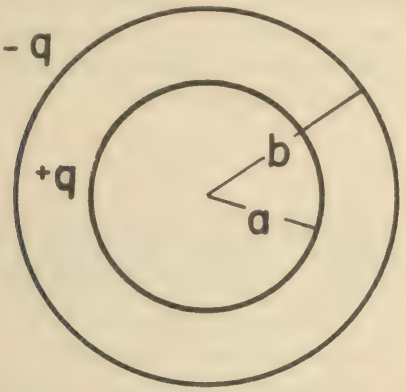

FIGURE 3–4.—Spherical condensers for theoretical consideration.

not change the electric field inside itself and consequently it has a potential q/b from Eq. (5). Then the two spheres have a difference of potential:

$$q\left(\frac{1}{a}-\frac{1}{b}\right)$$

Then, by 6):

$$C=\frac{1}{\left(\frac{1}{a}-\frac{1}{b}\right)}$$

$$=\frac{ab}{b-a} \qquad (8)$$

If now both a and b become very large in such a way that $(b-a)$ remains small, the curvature of the plates decreases and the construction approaches the usual parallel plate condenser:

$$C\cong\frac{a^2}{b-a}$$

If this is divided by $4\pi a^2$, the area of the sphere, the result will be the capacitance per unit area. Also let $(b-a)=s$, the plate separation. Then

$$C \text{ (per unit area)}=\frac{1}{4\pi s}$$

and for any area

$$C=\frac{A}{4\pi s} \qquad (9)$$

If the space between the plates is filled with a dielectric of specific inductive capacitance k the capacitance will be k times as large as calculated from Eq. (9). This is an important factor in constructing large condensers. Insulators such as paper, mica, or organic oils, have dielectric constants ranging from 2.5 to 5, and are frequently used in condenser construction. It should be noted that the capacitance of a condenser is not the amount of electric charge it can hold, because from Eq. (6) the quantity can be increased by increasing the potential difference. If the potential is increased too much, however, the dielectric will rupture and the condenser may be ruined.

So far electricity has been treated as if it were a completely divisible fluid capable of existing in any desired amount. Actually, this is not the case. Electricity is atomic in nature, and any charge will be an integral number of the elementary units. Millikan, in 1915, succeeded in measuring the charge by a simple method known as the oil drop experiment.

Millikan used two horizontal condenser plates,

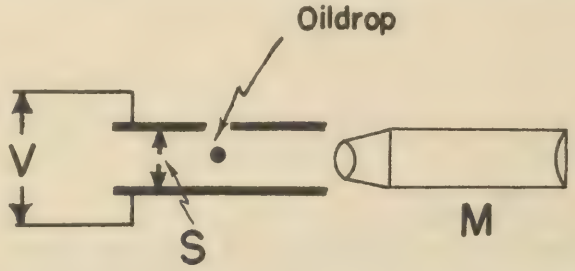

FIGURE 3–5.—The Millikan oil drop experiment. The oil drop will carry a charge picked up in the spraying.

separated by a distance S and connected to a potential difference V. A fine mist of oil was sprayed into the air above the top plate, and an occasional droplet would fall through a hole in the top plate and into the field of the microscope

M. In the process of spraying, most of the droplets became electrified and so were influenced by the electric field between the plates. If a unit charge is taken from one plate to another, the work done will be V ergs, and since the distance is S the force or electric field strength will be V/S. If an oil drop of mass m has acquired a charge q the downward pull of gravity will be mg, and the electric force will be Vq/S. If V is adjusted so that the drop remains stationary:

$$\frac{Vq}{S}=mg \tag{10}$$

All quantities except q can be measured. Millikan determined the charge on hundreds of oil drops. Many different values were found but in every case the charge was an integral multiple of 4.8×10^{-10} e. s. u. It appears, therefore, that this is the size of the elementary unit of electricity and no smaller quantity is known to exist.

A large number of experiments indicate that the unit of negative charge is carried by a small particle known as the electron. Positive charges are associated with matter and are demonstrated only when the normally neutralizing electrons are removed. An electron has a mass of only 9×10^{-28} grams, about 1/1840 the mass of the lightest atom, and moves about freely in electric fields. An electric current consists of a mass movement of electrons, the positive charges remaining fixed in their equilibrium positions. The strength of an electric current, I is equal to the amount of charge that passes a given point per second. That is

$$I=\frac{Q}{t} \tag{11}$$

I and Q will be measured in the same system of units.

3.02 Magnetism

The qualitative aspects of magnetic phenomena have been known for centuries, and magnets and magnetism are everyday experiences. Only a brief discussion is needed to establish the aspects of magnetism essential to the present discussion.

The concept of a magnetic pole is somewhat more complicated than the corresponding electric charge, because the existence of a single magnetic pole has never been demonstrated. If an iron rod is magnetized, one end will be a north pole and the other end will be a south pole. No amount of division or other treatment of the rod will result in a single isolated pole, and the conclusion is reached that the two poles are inseparable. It is sufficient for present purposes to consider the iron to be composed of tiny elementary magnets. In the non-magnetized state these have a random orientation which results in a neutralization. When magnetized, the elementary magnets line up, leaving an unneutralized pole near each end. By working with long thin rods it is possible to approach single pole conditions, since the interfering poles are placed at a considerable distance.

As in electrostatics, it is found that like poles repel and unlike poles attract, and that the force obeys an inverse square law:

$$F=\frac{+m_1m_2}{\mu r^2} \tag{12}$$

where μ is the magnetic permeability of the intervening medium. For most purposes, $\mu=1$ except in magnetizable materials such as iron and certain alloys. As in the case of electric charge, the unit of pole strength m can be defined to eliminate constants (except μ). The *unit magnetic pole* is then the *pole which is repelled with a force of one dyne by an equal pole one cm. distant in a vacuum.* This definition forms the basis for the electromagnetic system of units e.m.u.

If it is found that a magnet has a force exerted on it, there is a magnetic field at that point. The strength of the field is equal to the force in dynes exerted on a unit pole. The direction of the field is the direction of the force on a north pole.

A most important fact is that a wire carrying an electric current is surrounded by a magnetic field. The direction of the field will be perpendicular to the direction of current flow, and can be represented by a series of concentric circles around the wire. If the fingers of the right hand are curled as if to grasp the wire, and the thumb is extended along the wire in the direction of the current flow, the curled fingers will show the direction of the magnetic field.

The calculation of the field produced is made through the law of Biot and Savart. If a current I flows, the magnetic field strength at any point P will be the sum of the effects of small segments of the wire. The effect of each segment will be

proportional to the current, the length of the segment Δs, the sine of the angle θ between the segment and the line to the point P, and inversely proportional to the square of the distance r to P.

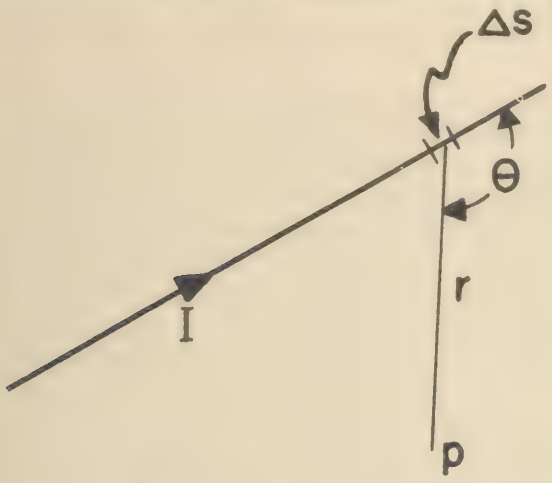

FIGURE 3–6.—The magnetic field at P will be due to the effect of all of the small segments, S. With the current direction the field at P will be into the paper.

That is

$$\Delta H \alpha \frac{I \text{ sine } \theta \Delta s}{r^2} \qquad (13)$$

A particularly simple case occurs when a wire carrying a current I is bent into a circle of radius r. See figure 3–7

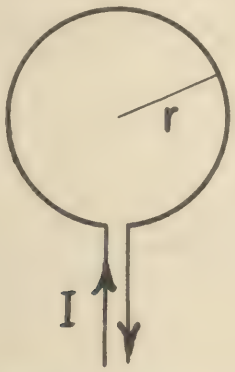

FIGURE 3–7.—The magnetic field due to a circular coil. The field inside the coil will be directed into the paper.

Then for each segment sine $\theta = 1$,
and the summation of Δs is equal to one circumference of the circle or, $2\pi r$. Then

$$H \alpha \frac{2\pi r I}{r^2} \text{ or } \alpha \frac{2\pi I}{r} \qquad (14)$$

Since the unit of current in this system has not been defined, it seems reasonable to replace the proportionality by an equality and use Eq. (14) to define the *e.m.u. of current* (*abampere*)

$$H = \frac{2\pi I}{r} \qquad (15)$$

In passing, it may be noted that 1 abampere = 10 amperes, the latter being the unit of current in the practical system. The magnetic field strength, H, which is in dynes per unit pole, is expressed in oersteds.

It is obvious from the derivation of Eq. (14) that if n turns of wire are used, H will be n times as large, and thus many turns of wire are used to obtain strong magnetic fields. To produce still stronger fields, an iron core may be put inside the coil. The magnetic field produced by the coil will magnetize the iron, and this will increase the total magnetism or magnetic flux, ϕ, produced by the current. The flux per unit area, B_1, is somewhat analagous to the field strength H_1, and a plot of B against H will show the gain in magnetism obtained by the use of iron. Figure 3–8 shows such a B–H plot, or magnetization curve.

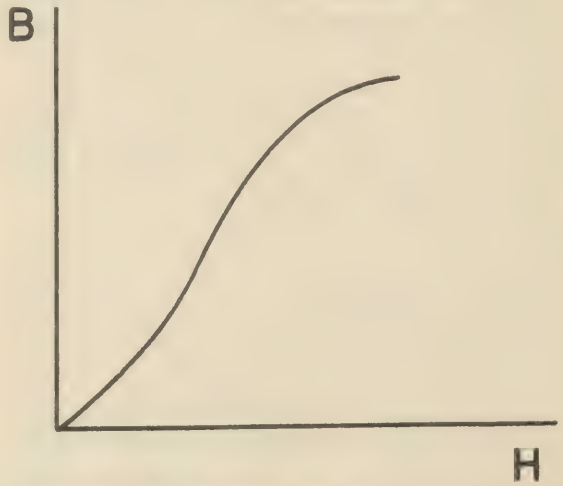

FIGURE 3–8.—The magnetic curve for iron. The curve is not strictly correct as the exact shape depends on the previous magnetic history of the iron.

Although the magnetism can be increased by the use of iron, it no longer depends linearly on I as it does in air, Eq. (15). This was to be expected from the assumption that the iron is made up of tiny elemental magnets. For example, the saturation effect shown in figure 3–8 is explained by the fact that the elemental magnets have been com-

pletely rotated, and any further increase in H can not produce further rotation. Another disadvantage of iron is the heating effect produced when the direction of the field is rapidly changed There are several reasons for this heat production. One source comes from the fact that the elementary magnets appear to move in a viscous medium and the resulting frictional losses produce considerable heating. If an alternating current is sent through a coil it is necessary to construct the core of thin sheets of special alloys so that the heat loss is kept within reasonable bounds.

3.03 Electrical Conduction

The magnetic effects of an electric current have been discussed above without any particular reference to the mechanism of conduction of the current. This mechanism will now be considered for solids, liquids, and gases, each medium having features quite different from the other two.

The use of metal wires for conducting electric currents is well known, and the use of other materials as non-conductors or insulators is equally important. The present conception of a metal is as an aggregate of atoms rigidly bound into a more or less regular crystal structure. These atoms are immobile and do not take any active part in the conduction. In addition to the bound atoms, the metal contains a large number of free electrons, about one for each atom. These electrons form a sort of electron gas (Sec. 2.07) and have a thermal motion much like kinetic motion of gas molecules.

When a potential difference is applied to the ends of a wire, an orderly motion is superimposed on the random motion of the electrons and an electric current flows. The velocity of the conduction electrons is low, but the rate of propagation of the electric force along the wire has a velocity almost equal to the velocity of light. Therefore the conduction takes place almost instantaneously.

As the free electrons move under the acceleration of the applied potential, they will suffer frequent collisions with the rigidly bound atoms. At each collision, the electron will lose energy, will then again be accelerated, and will again collide and lose energy. The situation is analagous to the mean free path in kinetic theory.

Since energy is lost at each collision, heat will be developed in the wire, and a potential difference will be required to maintain the current. Ohm showed experimentally in 1826 that the potential difference is proportional to the current. This is written:

$$V=IR \tag{16}$$

where R is the resistance of the conductor. This equation, which is known as *Ohm's law*, is applicable in any system of electrical units, but only the practical system is ever actually used. With V in volts and I in amperes, R will be expressed in ohms. This equation can be applied to any circuit or portion of a circuit remembering that the resistance R will be that between the points at which the difference of potential is measured.

Measurements show that the resistance of a conductor is proportional to its length and inversely proportional to its cross-sectional area. Thus:

$$R=\rho\frac{l}{A} \tag{17}$$

where l is the length and A is the cross-sectional area. ρ is a constant characteristic of the material, known as the *specific resistivity*. Table I shows the enormous variations in ρ found in common substances. It should be noted that for most materials ρ increases with temperature.

TABLE I.—*Specific resistivity*

Material:	*Ohm-cm*
Copper	1.7×10^{-6}
Aluminum	2.8×10^{-6}
Iron	1×10^{-5}
Carbon	3×10^{-3}
Amber	5×10^{16}
Quartz	5×10^{18}

Since there is a potential difference V across the ends of a resistor, the electrical work done W will be

$$W=VQ \tag{18}$$

where Q is the total quantity of electricity transported. This will be exactly equal to the heat developed in the resistance. It is more customary to express this as the rate at which heat is developed by replacing Q by the current I. In which case

$$P=VI \tag{19}$$

where P will be in watts or joules per second, if V is in volts and I is in amperes. If V and I are

both expressed in either e.s.u. or e.m.u., the power P will be in ergs per second. Eq. (19), which is known as *Joule's law*, may be transformed by an application of Ohm's law into two other useful forms:

$$P=I^2R \tag{20}$$

and

$$P=\frac{V^2}{R} \tag{21}$$

Any of the three forms of Joule's law may be used.

In addition to the consistent units which are usually used in Eq. (18) to obtain the work in ergs or joules, there is one inconsistent combination commonly used in nuclear physics. The introduction of such a hybrid unit can only be justified by its practicality. If a charge equal to one electronic charge is accelerated by a potential of one volt, the work done is known as one *electron volt*. Since V in volts times Q in coulombs yields W in joules, and since the electronic charge is 1.6×10^{-19} coulombs—one electron volt

$$\begin{aligned}(\text{ev})&=1.6\times10^{-19}\text{ joules}\\&=1.6\times10^{-12}\text{ ergs}\end{aligned} \tag{22}$$

A second frequently used unit is the million electron volt (Mev) which is obviously

$$1\text{ Mev}=1.6\times10^{-6}\text{ ergs} \tag{23}$$

In all circuits used for measuring radiation, many resistors are used with resistance values ranging from 1 to 10^{11} ohms. Resistances below about 10^8 ohms present no particular probem. For precision work or where stability is essential wire wound resistors are available in values up to 10^6 ohms. Thin metal deposits or graphite films may be used where extreme stability is not required. Above 10^8 ohms, however, the construction and mounting becomes important. Leakage across the resistor terminals can then have a resistance comparable to that of the resistor itself, and since this may be variable depending on humidity and other conditions, great care must be taken to reduce surface leakage. High resistance units are now available, mounted in a vacuum in glass containers whose surfaces are especially treated to reduce surface leakage. These units must be handled carefully, as fingerprints may spoil the surface coating.

In some instruments it is necessary to use the very best insulating materials to insure proper operation. Outstanding insulators are quartz, sulphur, amber, and polystyrene. Whenever these materials are used they must be handled with great care to avoid surface leakage. Instruments requiring these insulating materials are described in chapter 9.

The effects of moisture on high resistors have been mentioned above, where it was implied that aqueous solutions are relatively good conductors. This is indeed the case, but the mechanism of liquid conduction is quite different from that of metallic conduction.

Imagine some compound such as silver nitrate, $AgNO_3$, dissolved in water. Now water has a dielectric constant of about 80, and hence by Eq. (1) the electrical forces holding a molecule together will be reduced by a factor of 80. The forces are no longer adequate, and most of the molecules will split into two charged portions or ions, Ag^+ and NO_3^-, the + and − signs showing the electric charge carried by each ion. Thus Ag^+ indicates that one of the electrons needed to obtain neutrality is missing, and NO_3^- indicates that the ion has one extra electronic charge.

If two electrodes are immersed in the solution and a potential difference applied, the ions will be attracted, each to the oppositely charged electrode. The Ag^+ ions will move to the negative electrode, or cathode, where each ion will acquire an electron and become a neutral silver atom, which will be deposited on the cathode. This is the basis of the process of electroplating. The electrons required for neutralization must be supplied by the external source of potential, and hence a current flows in the circuit. The solution exhibits a resistance but this is a complicated function of the concentration of the solution and the temperature and is of no immediate interest. It is the relation between the flow of electric charge and the mass of metal deposited that is of importance.

About 1835 Michael Faraday announced the fundamental laws governing liquid or electrolytic conduction. The mass of metal deposited depends only upon the quantity of electricity which flows, and not upon current, voltage, solution concentration, or any other variable. The amount of any chemical element deposited by a given quan-

ity of electricity is proportional to the atomic weight of the element. In particular 96,500 coulombs of electricity will deposit 107.88 grams or one gram atomic weight of silver. The atomic weight of copper is 63.57 and it is found that only 63.57÷2 grams are deposited by 96,500 coulombs. This strongly suggests that silver is present in the solution as Ag^{+}, needing only one electron for neutralization, while copper is ionized as Cu^{++}, and thus yielding only one-half of the deposit per coulomb. The number of charges on each ion is equal to the valence of the element.

The quantity, 96,500 coulombs, is known as the *Faraday*. It can be determined quite accurately and by combining it with the results of the Millikan oil drop experiment it is possible to calculate Avogadro's number. The electronic charge is 1.6×10^{-19} coulombs and so one Faraday will neutralize

$$\frac{96{,}500}{1.6\times10^{-19}}=6.1\times10^{23} \text{ charges}$$

Since the Faraday will neutralize 107.88 grams or one gram atom of silver, it is evident that one gram atom of silver contains 6.1×10^{23} atoms which is Avogadro's number. The same value will be obtained for any other element if the proper valence is taken into account. These experiments indicate clearly that matter as well as electricity is atomic in nature and can be divided down to elementary unit structures. In the case of matter the unit structure is different for each element, but the electron has the same properties wherever it is found.

A further insight into the structure of matter is obtained by considering the conduction of electricity through gases. At pressures of one atmosphere or higher, all gases are excellent insulators and only extremely high voltages can produce an appreciable current flow. At low pressures the situation is quite different, as is readily seen by the neon and mercury signs in our cities. A series of complex phenomena take place at pressures of about 1 mm of mercury. A complete description of these phenomena is not possible nor necessary: only the essential features of the mechanism will be described.

If a potential is applied to electrodes in a gas, any stray charges in the gas space will be accelerated toward the proper electrode. At high pressures the mean free path (sec. 2.07) will be short, and the energy acquired by the accelerated charges will be dissipated in a large number of collisions. At low pressures, the mean free path becomes large, and a charge can attain a considerable kinetic energy before experiencing a collision. If it has sufficient energy, a charge will split up or ionize a gas molecule upon collision. The ions into which a neutral molecule is split are charged, and each will be attracted toward the proper electrode and produce further ionization by collision. Ions reaching the electrodes are neutralized and are then available for further ionization. Thus a discharge started by a stray charge will continue as long as a potential is applied to the electrodes. The discharge in gases is of great importance in radiation measuring instruments and in the production and study of molecular beams and will be discussed in detail in chapters 7 and 9.

It is to be noted that the mechanism of ionization in a gas is quite different from that in the case of electrolytic conduction, where ionization by collision plays no part. No attempt is made to determine the resistance of the gas as this is a complex function of the kind of gas, the pressure, and the current. In fact, because of the cumulative ionization, the current may tend to increase to a very high value unless limited by external means. If the current through the discharge increases, there will be an increase in the number of ions, and because of the better conduction the voltage may drop and the discharge show a negative resistance.

If the discharge does take place as described, there should be a stream of negatively charged particles moving toward the positively charged anode, and a stream of positive ions moving toward the cathode. The negative particles, coming from the vicinity of the cathode, were originally called cathode rays. They are now known to be electrons moving with high velocity. They have the same properties regardless of the gas in the tube, and these properties are the same as found for electrons from quite different sources.

The positive ions have a much greater mass and it is now certain that they are the positively charged residues of atoms from which one or more electrons has been removed by collision. The positive ions are best studied by separating them from the electron stream. This was originally done by

boring holes in the cathode to allow the ions to pass through into a discharge-free region. The ions were originally known as canal rays because of this arrangement. (See chap. 5, fig. 5–1.)

3.04 Electronics

In the previous section the phenomena accompanying the passage of electricity through gases were briefly described. If the gas pressure in a discharge tube is reduced by continued evacuation, the discharge will stop when there is no longer a sufficient number of gas molecules to provide the ions necessary for conduction. With a very high vacuum and with cold electrodes the tube becomes a very good insulator, and no appreciable current will flow even when many kilovolts are applied to the electrodes.

If one electrode is hot, as would be a filament of fine wire carrying a current, the situation is quite different, and currents will pass through the vacuum to a cold electrode with potentials of only a few volts. Such a device forms the basis of the modern vacuum tube, a very powerful tool that is used in many instruments in nuclear physics and radiological safety measurements. The fundamental construction of a two element tube or *diode* is shown in figure 3–9.

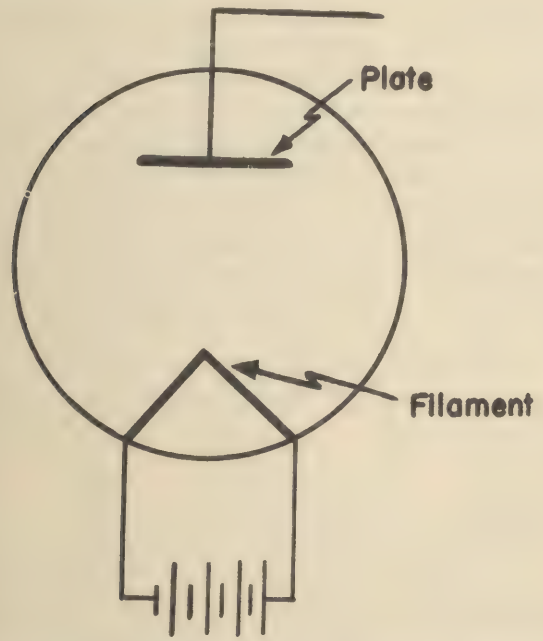

FIGURE 3–9.—A 2-element tube, or diode, with electron emission from a hot filament.

When the temperature of the metal *filament* is raised the average kinetic energy of its free electrons will be increased, and some of them near the surface of the wire will acquire sufficient velocity to escape from the metal into the surrounding empty space. With no potential on the cold electrode or *plate*, there is no electric field in the space around the filament, and the escaped electrons will remain close to the filament and form a space charge. As the filament loses electrons, it becomes positively charged, and this will attract some of the electrons back into the metal so that a state of equilibrium exists with a constant space charge. The amount of *space charge* obviously depends on the filament temperature, but in all of the following discussion this will be assumed constant at the value recommended by the manufacturer of the tube. In many tubes the electrons are not emitted directly from the filament but from an indirectly heated cathode. This is a thin metal cylinder surrounding a ceramic tube. The filament inside the cylinder merely serves to heat the cathode and does not enter into the electrical function of the tube. The cathode surface is usually coated with various oxides to obtain a copious electron emission at low temperatures.

If the plate is made negative with respect to the filament, the space charge will be repelled, and no current will flow in the tube. When the plate is positively charged, some of the space charge electrons will be attracted to the plate, and a current will flow through the tube. Thus the current flow in a tube is unidirectional. If an alternating potential is applied to the plate the tube will conduct only on the positive halves of the cycle and acts as a *rectifier*. The use of diodes in radiological safety apparatus is almost entirely confined to the rectification of alternating current from power lines to provide direct current for various purposes.

The introduction of a third electrode or *grid* in the space charge region forms a *triode* and is the basic construction for all modern amplifying tubes. The grid consists typically of a spiral of fine wire closely surrounding the cathode. The electrons can pass freely from the cathode to the plate, but they will be strongly influenced by the potential of the grid.

The operation of a triode can best be described by a discussion of the *characteristic* curves obtained from the circuit of figure 3–10. If the plate volt-

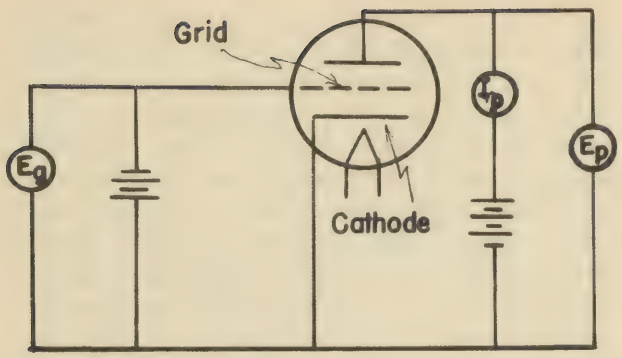

FIGURE 3–10.—Circuit for obtaining the characteristics of a triode.

age E_p is held constant and the grid voltage E_g is varied the values of the true plate current I_p can be plotted against E_g as is figure 3–11. When the grid is strongly negative all electrons are repelled to the cathode, no current flows and the tube is said to be *cut off* (point *A*). As the grid becomes less negative some current flows and the characteristic shows a linear portion *BC*. When the grid becomes positive, every emitted electron is attracted from the space charge and the tube is *saturated* (point *D*).

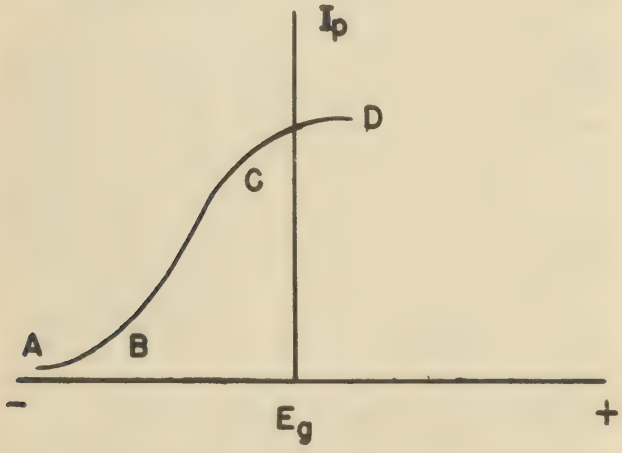

FIGURE 3–11.—Mutual characteristics of a triode.

The linear portion of the characteristic lies entirely on the negative side of the grid voltage axis. This is an important region because here the variations in plate current will accurately follow the variations in grid voltage. Over the curved portions of the characteristic the variations in plate current do not vary linearly with grid voltage.

The importance of the grid lies in two main features:

(*a*) Over the linear portion of the charcteristic the grid can control the plate current but draws practically no current. In this region the grid current will not exceed 10^{-8} amperes and may be as low as 10^{-15} amperes. Thus the power input to the grid is very small, yet the grid can control substantial amounts of plate current power.

(*b*) A change in grid voltage will have as great an effect on the plate current as a much larger change in plate voltage. For example, a change of grid voltage of 1 volt might change the plate current by 3 milliamperes, whereas the plate voltage would have to be changed by 100 volts to produce the same change in plate current. Since 1 volt on the grid has the same effect as 100 volts on the plate, the tube has an *amplification factor* of 100. It is this ability of a triode to amplify small signals that makes it such a powerful tool.

When vacuum tube circuits are examined, more complicated types of tubes will be found, but in general the fundamental action will be the amplifying effect of the triode. Five element tubes or pentodes are used in place of triodes when high amplification factors (up to 1,500) are desired, but the two additional grids are maintained at constant potentials and do not enter into the amplifying of the signal impressed on the grid. More complex tubes are constructed for radio use but are not of immediate interest.

If it is desired to obtain a voltage output from a tube instead of a plate current change, resistance must be inserted in the plate circuit. (See fig. 3–12.) A constant voltage E_B is applied to the plate through resistor R and E_c is adjusted to bring the tube to the desired operating point on

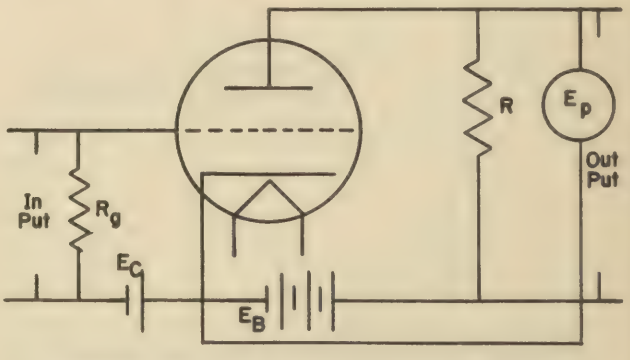

FIGURE 3–12.—The triode as a voltage amplifier.

its characteristic curve. This will usually be at the center of the linear portion BC of figure 3–11. Suppose now a small positive signal voltage appears across R. The grid voltage will then become less negative and the plate current will increase. But if the plate current increases, the voltage drop across R_g will increase by Ohm's law and hence the plate will become less positive. Thus the positive input signal has become an amplified negative signal. This phase reversal is important when tubes are used in Geiger counter circuits where pulses of one polarity are received from the counter tubes.

Before leaving vacuum tubes it should be noted that the action is nearly instantaneous. The time of passage of an electron from cathode to plate is of the order of 10^{-10} seconds, and hence a grid signal appears with almost no delay in the plate circuit. Only in special applications is the time lag of practical importance.

3.05 Forces on Moving Charges

Electric and magnetic fields exert forces on moving charges and these forces can best be studied in the gas discharge, for here the charges are free from the restraint of a conducting wire.

The case of the electric field is a simple one. The force on the charge is Ee and is in the direction of the field. It is independent of the velocity of the charge. The field strength E is usually easily determined from the dimensions of the apparatus. If the field is produced between parallel plates, $E=V/s$ as in the Millikan oil drop experiment.

It is easy to see qualitatively that when a magnetic field acts on a moving charge, the force produced will be at right angles to both the magnetic field and the velocity of the charge. To obtain the quantitative relations consider again the circular coil of wire shown in figure 3–7. From Eq. (14) the magnetic field strength at the center of the coil is

$$H=\frac{2\pi I}{r} \tag{24}$$

From the definition of H this will be the force exerted on a unit magnetic pole at the center.

Now by Newton's third law, if there is a unit magnetic pole at the center there will be a force of reaction on the wire, and this will be equal to

$$F=\frac{2\pi I}{r} \tag{25}$$

This force may be thought of as the action of the magnetic field of the unit pole at the center on the current I. The field strength of the unit pole is by Eq. (12):

$$H=\frac{1}{r^2} \tag{26}$$

and since each portion of the coil finds itself in this field, $1/r$ in Eq. (25) may be replaced by Hr from Eq. (26) and

$$F=2\pi rIH$$

Since $2\pi r=l$ (the length of the wire in the field) this reduces to:

$$F=HIl \tag{27}$$

As can be seen from figure 3–13, the force F is perpendicular to both the direction of I and H.

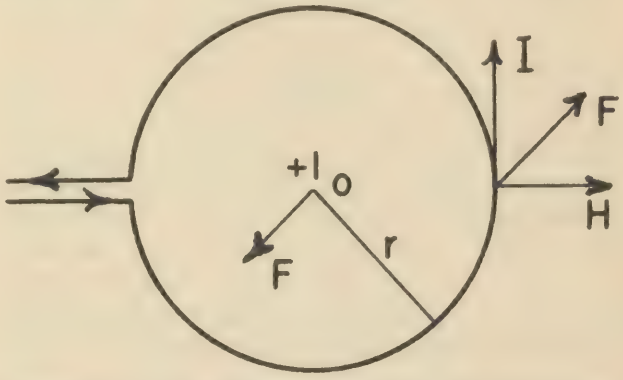

FIGURE 3–13.—A unit magnetic pole at 0 will have a force acting on it and by Newton's Third Law there must be an opposite force on the wire.

The force F will be in dynes if H and I are expressed in e. m. u. and l is in cm. This is a most important equation and forms the basis of all electric motor designs, for F is precisely the force which is utilized to obtain useful work from motors.

For present purposes, however, it is desirable to transform Eq. (27) slightly to obtain the force on a single moving charge rather than on an electric current in a wire. By definition, the current I consists of I units of electric charge flowing past any given point in the wire per second. If each of the charges is moving with a velocity v, all of the charge in v cm of wire will flow past in one second. There are, then I/v charges per cm. of wire, or Il/v charges in l cm. of wire. But Eq.

(27) gives the force on l cm. of wire, so the force per unit charge is:

$$F=\frac{HIl}{\frac{Il}{v}}$$

$$=Hv$$

The force on a charge will then be:

$$F=Hev \qquad (28)$$

where e must be in e.m.u. v in Eq. (28) has the same direction as I in Eq. (27), and consequently F is perpendicular to v. This is precisely the condition necessary for circular motion (sec. 2.03), and consequently a charge moving in a magnetic field will move in an arc of a circle, or in a complete circle if the field is strong enough. Setting the magnetic force equal to the required centripetal force:

$$Hev=\frac{mv^2}{r}$$

or

$$\frac{e}{m}=\frac{v}{Hr} \qquad (29)$$

The ratio e/m is a very important property of charged particles. There are various methods for measuring all of the quantities on the right-hand side. When this is done for electrons, the ratio e/m turns out to be 1.77×10^{7} e. m. u. per gram. Since the oil drop experiment showed that the electronic charge is 1.6×10^{-20} e. s. u.:

$$\text{mass of electron}=m=\frac{1.6\times10^{-20}}{1.77\times10^{7}}=9\times10^{-28}\text{ grams}$$

By this type of measurement the masses of all types of charged particles can be determined to a high accuracy.

3.06 Electrical units

It will be noticed that three consistent systems of units have been introduced, and a unit of work, the electron volt, belonging to no particular system, has been added. All of this may seem like an unnecessary complication. Actually it is not, and all attempts to simplify the electrical systems have been unsuccessful. The fundamental difficulty lies in the fact that electric charge and magnetic poles are quite different things which require separate definitions and yet must be brought together because of the interaction between them. In Table II the relations between the various systems are collected for convenient reference. Some of the electrical quantities not needed in the present text have been omitted.

TABLE II

Quantity	Practical	E. S. U.	E. M. U.
Charge (Q)	1 coulomb	$=3\times10^{9}$ statcoulombs	$=10^{-1}$ abcoulombs.
Current (I)	1 ampere	$=3\times10^{9}$ statamperes	$=10^{-1}$ abamperes.
Potential (V)	1 volt	$=1/300$ statvolt	$=10^{8}$ abvolts.
Resistance (R)	1 ohm	$=1/9\times10^{11}$ statohm	$=10^{9}$ abohms.
Capacitance (C)	1 farad	$=9\times10^{11}$ cm	$=10^{-9}$ abfarads.
Magnetic field (H)	1 oersted	$=1/3\times10^{9}$ statoersted	$=10$ aboersteds.

Work and energy

V (e. s. u.) $\times$ Q (e. s. u.) = ergs.
V (e. m. u.) $\times$ Q (c. m. u.) = ergs.
V (prac.) $\times$ Q (prac.) = joules.
V (prac.) $\times$ Q (electrons) = electron volts $=1.6\times10^{-12}$ ergs.

Chapter 4

ELECTROMAGNETIC WAVES

4.01 General Properties of Waves

It is easy to visualize the transmission of energy by fast moving particles which can give up their kinetic energy upon collision with stationary targets. Less obvious, but equally important is the transfer of energy by wave motions. All of the sun's energy reaching the earth is transmitted by electromagnetic waves, all audible sounds are transmitted by sound waves, and some of the greatest nuclear radiation hazards arise from short wave length electromagnetic waves. It is therefore necessary to inquire into the nature of waves in general, and electromagnetic waves in particular.

The general concept of wave transmission is a simple one. Some type of transmitter vibrates and sets up strains in the surrounding medium. The medium, in attempting to return to its original unstrained state, propagates the strains which travel out from the source and act on some suitable receiver. Thus, when human vocal chords vibrate, a succession of pressure impulses are applied to the surrounding air. Pressures above and below normal exist and are transmitted by each small volume of air to the volume immediately beyond. The pressure variations travel out from the source, and when they strike an eardrum, it is set into vibration and a sound is heard.

It should be noted that the medium transmitting the waves does not move from source to receiver. A disturbance of the medium does travel but the medium itself does not move appreciably. A stone thrown into a quiet pool will produce a series of waves which spread out in concentric circles from the source of the disturbance. A cork floating on the surface bobs up and down as the waves pass, but it does not move outward from the source as it would if there was an actual outward flow of water.

The most obvious property of a wave is its *frequency* or number of vibrations per second, denoted by the Greek letter ν. Frequency is really to be associated with the source of the disturbance since the wave is merely the transmission of the disturbance. The frequency of the wave is, of course, the same as the frequency of the source.

It is sometimes more convenient to use the time of one vibration, T, also known as *period*, instead of the frequency. The two are related by the equation

$$\nu = \frac{1}{T} \tag{1}$$

Since a wave is propagated, there will be a velocity, v, associated with the wave motion. The velocity is a property of the medium and not of the source, for once the disturbance has been transmitted to the medium it is independent of the behaviour of source. This text is concerned almost exclusively with electromagnetic waves which have a velocity in a vacuum of 3×10^{10} cm. per second, denoted by c. This is one of the fundamental constants of nature which appears frequently in many unexpected places.

If a source is vibrating steadily with a frequency ν and the velocity of wave propagation is c, at the end of one second there will be ν waves spread over a distance c in space. One wave will occupy a distance λ, where

$$\lambda = \frac{c}{\nu} \tag{2}$$

The distance λ, or *wave length*, is the shortest distance between consecutive similar points on the wave train. Thus it is the distance between consecutive crests or peaks, or consecutive troughs, figure 4–1.

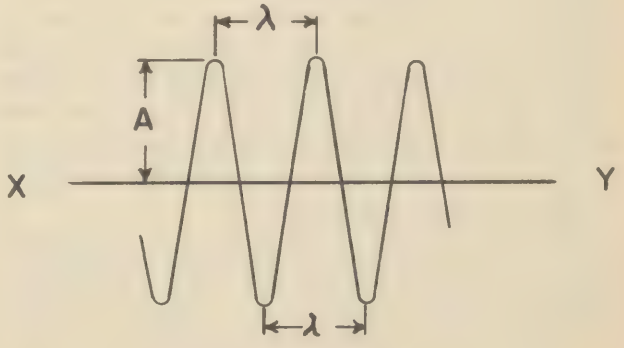

FIGURE 4–1.—Amplitude and wave length in a wave motion.

Figure 4–1 illustrates another characteristic of wave motion; namely *amplitude*, *A*. *XY* represents the undisturbed position of the medium, and as shown the amplitude is the distance from this undisturbed position to a point of maximum displacement. In an electromagnetic wave there is no actual displacement of a medium, and the concept of amplitude is a little more abstract, but can be thought of as the maximum strain in the medium. As might be expected, the amplitude is closely related to the energy carried by the wave.

If a source starts a wave motion in the surrounding medium, the waves will in general spread out uniformly in all directions. Consider again the case of a stone thrown into a quiet pool. If at some later time, an instantaneous photograph is taken of the water, a series of concentric rings of maximum upward displacement (crest) will be observed, and in between these there will be a series of concentric rings of maximum downward displacement (trough). Each circle drawn through points having the same displacement (or phase) is known as a wavefront. The wavefronts move out from the source as the wave proceeds. At every point the direction of propagation is perpendicular to the wavefront. Lines drawn in the direction of propagation are called rays. Figure 4–2 shows the situation for the water waves described above. *U*, *U′*, *U″* are wavefronts of maximum upward phase; *D*, *D′*, *D″* are wavefronts of maximum downward phase; and *R*, *R′*, *R″* are rays.

There is sometimes a confusion in terminology between waves and rays. Thus it has become customary to speak of radio waves and X-rays. Actually each is a wave motion, having both wave fronts and rays. It should also be noted that in the older literature, the terms, "alpha ray" and "beta ray" are commonly used. These are now known to be high speed particles and so should be called, respectively, alpha particles and beta particles, rather than rays.

All wave motion exhibits certain phenomena when it strikes a new medium. One of these is *reflection*. (See fig. 4–3.) If a bundle of rays, *A*, *A′*, and *B*, *B′*, with a wave front *AB*, strike a reflecting surface, the ray *A′* will be reflected, while *B′* still has to travel to *B″*, before being reflected. The result will be a bundle of rays

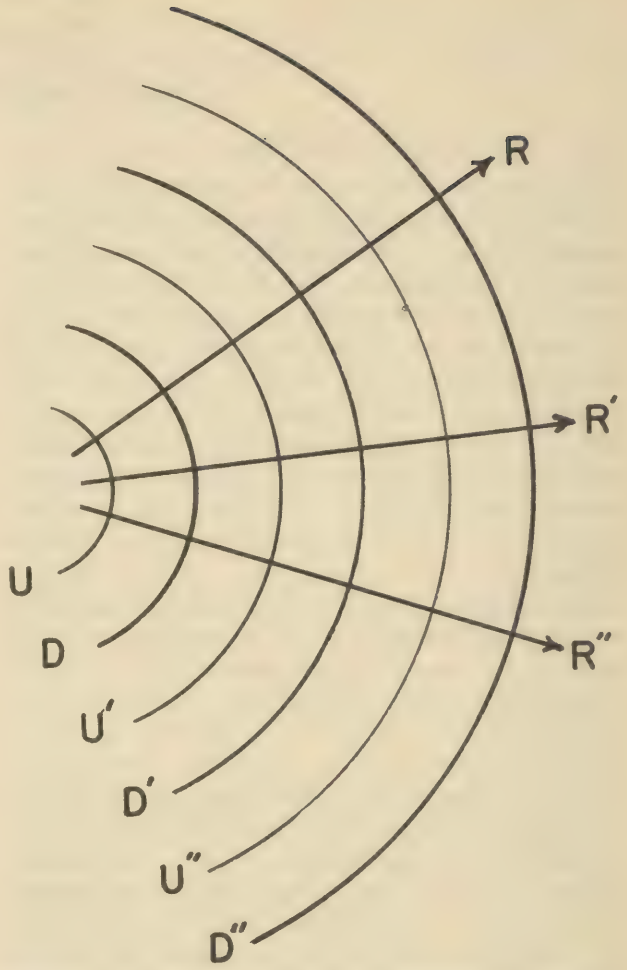

FIGURE 4–2.—The relation between wave fronts and rays.

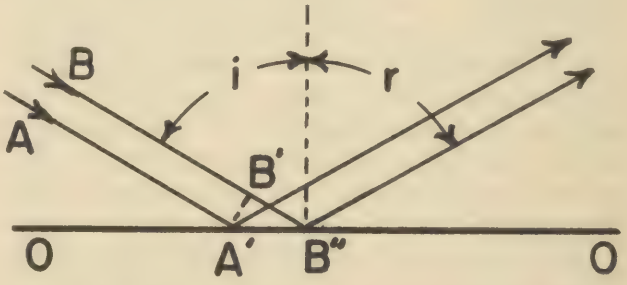

FIGURE 4–3.—Reflection of light at a plane surface. The angle of incidence *i* is equal to the angle of reflection *r*.

reflected so that the angle of reflection, *r*, is equal to the angle of incidence, *i*. All waves exhibit reflection, but all phenomena showing reflection are not necessarily waves. For example a tennis ball, neglecting other external forces, will bounce off a wall with an angle of reflection equal to the angle of incidence.

Wave motions are *refracted* when they enter a new medium having a different velocity of propagation. Figure 4–4 shows a bundle of rays entering a medium of slower propagation. While B' travels to B'' in the old medium, A' travels the shorter distance to A'' in the new medium. Thus the rays in the new medium will proceed with a new direction A', A'', A'''. Refraction is also exhibited by motions other than waves.

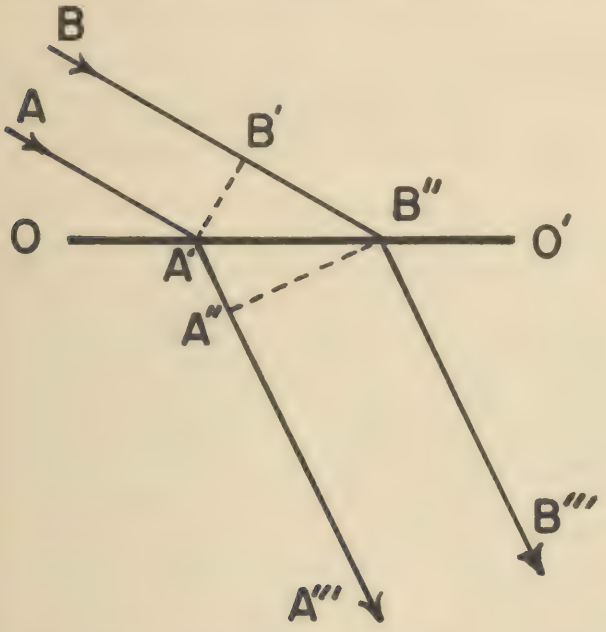

FIGURE 4–4.—The refraction of light into a medium of slower propagation. The refracted rays make a smaller angle with a perpendicular to the surface.

Diffraction and *interference*, however, are phenomena which are unique to wave motions. If two waves of equal wave length, but opposite phase, are superimposed, crest will fall on trough; the combined additive effect will be a complete cancellation, and the two waves are said to interfere destructively. If the two superimposed waves are in phase, crest will fall on crest, an increased intensity will result, and the two waves show constructive interference. It is extremely difficult to conceive of particles showing constructive or destructive interference. Interference is most easily demonstrated through the diffraction or bending of waves in passing through small openings. Consider a wave front, AB, of visible light, striking a diaphragm with two small openings or slits S_1 and S_2 (fig. 4–5). Only a small portion of

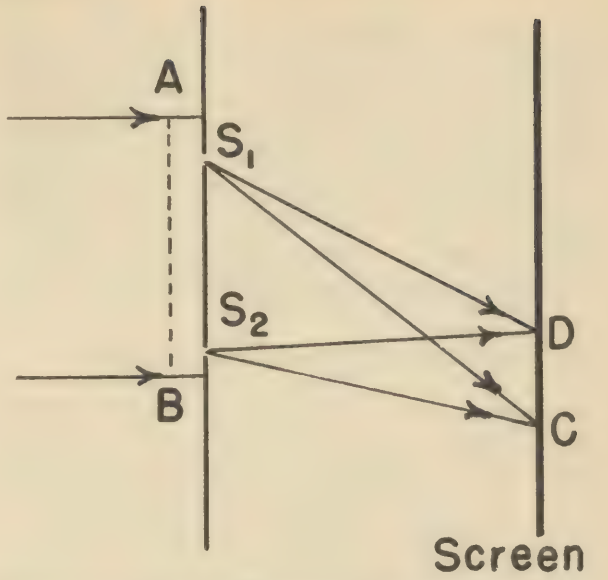

FIGURE 4–5.—The interference of light passing through narrow slits.

the wave front will enter each of the slits. Because of diffraction these small portions of the wave front will spread out in hemispherical waves after passing through the slits. If a point C on the screen is so chosen that the distance S_1C is exactly one wavelength greater than S_2C, there will be constructive interference and light will be seen at C. If, again, S_1D is one half wavelength greater than S_2D, there will be destructive interference and no light will be seen at D. Thus a series of light and dark bands will appear on the screen.

It is evident that this experiment serves not only to demonstrate the wave nature of light, but can be used to measure the wavelength. The wavelength of visible light is only about 5×10^{-5} cm. and consequently diffraction is small and can be seen only in specially designed equipment. The wavelength of sound, however, is about 30 centimeters, the angles of diffraction are large, and sound readily travels around corners. There is only a small diminution in sound intensity when a speaker turns his back; if he has a flashlight in his hand, the reduction in light intensity will be to zero.

The wave properties described are very general and hold for any type of wave motion. Waves may be classified in many ways, the most common being on the basis of the direction of the displacement. In a sound wave, the small to-and-fro motions of the air molecules are along the direction of

propagation. This is called a *longitudinal* wave. If the end of a rope is given a displacement sideways, a wave will travel down the rope, but the direction of propagation is at right angles to the displacement and the wave is *transverse*. The most common example of a transverse wave is visible light, which is one member of the family of electromagnetic waves. The remainder of this chapter will deal exclusively with electromagnetic waves.

4.02 Properties of Electromagnetic Waves

In chapter 3 it was shown that moving electric charges produce a magnetic field, and conversely that a changing magnetic field produces an electric field. It appears, therefore, that the two types of fields are closely linked, and that if one exists the other will also be present. In a radio antenna, electric charges are accelerated back and forth, along the wire. This produces a changing electric field in the vicinity of the antenna, which in turn produces a magnetic field, and so an electromagnetic wave is propagated outward from the antenna. The identification of similar waves with visible light was first made by Maxwell. The predictions made by Maxwell in this connection have been verified by many experiments.

An electromagnetic wave consists of an oscillating electric field and an oscillating magnetic field, both at right angles to the direction of propagation. Each component vibrates with the same frequency, and in free space the two components are in phase (fig. 4–6).

The frequency of the wave depends upon the source emitting the energy, and an enormous range of frequencies is now known. This fact will be discussed more fully below. It is found, however, that the velocity of propagation in free space is independent of the frequency. For all but the most exact calculations 3×10^{10} cm. per second is a sufficiently accurate value. It is perhaps not surprising that a constant velocity is observed. The velocity of a wave motion depends on the properties of the medium and the nature of the wave being produced. All electromagnetic radiation is alike in that it consists of an oscillating electric field and an oscillating magnetic field. The same type of strain therefore appears in the medium at every frequency, and a constant velocity might be expected.

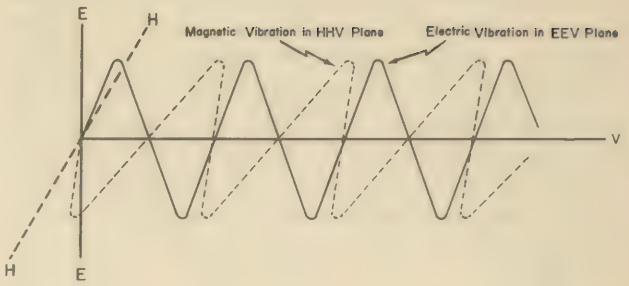

FIGURE 4–6.—The electromagnetic wave in free space. The electric and magnetic vibrations are at right angles to each other and to the direction of propagation.

The term *free space* has been used several times without definition: it is understood to mean space devoid of all demonstrable matter: i. e., a perfect vacuum. A sound wave, consisting of variations in air pressure, cannot be transmitted by a vacuum; but an electromagnetic wave is propagated without loss in the highest attainable vacuum. It is difficult to conceive of a wave being propagated without a propagating medium. What then is the medium which transmits electromagnetic radiation?

This problem was a serious difficulty in physics for many years. The medium was known as the luminiferous aether, or simply ether. Some of its properties could be predicted but it was never isolated or identified. Interest in the ether gradually waned and at present the experimental fact is accepted: electromagnetic waves can travel through free space and at a velocity independent of frequency.

When electromagnetic waves travel in a recognized medium they do not necessarily proceed with the velocity c; actually the velocity varies with frequency. The variation of velocity with frequency is known as dispersion, and this is responsible for the dispersing or separating of a beam of white light into its component frequencies by a glass prism. Blue light travels slower than red light in glass, and as a result blue light suffers more refraction or bending in passing through the prism. It is important to remember that there is no known way of preventing the propagation of electromagnetic waves by removing the propagating medium, as can be done for sound waves.

4.03 The Electromagnetic Spectrum

The known electromagnetic radiations may be arranged on the basis of frequency or wavelength into the electromagnetic *spectrum*. (Table I and fig. 4–7.) The spectrum is divided into several regions but it must be realized that the divisions are arbitrary and not at all rigid. In the main, the divisions are based on the methods used to produce the radiation, and it is quite possible to produce a given frequency by two or more methods. It is, for example, possible to produce by gaseous discharge ultraviolet radiation having a wavelength of 10^{-6} cm. This

TABLE I.—*The electromagnetic spectrum*

Type of radiation	Frequency range (per second)	Wave length range (cm.)
Electric waves	0–10^{4}	∞–3×10^{6}
Radio waves	10^{4}–10^{11}	3×10^{6}–0. 3
Infra red	10^{11}–4×10^{14}	0. 3–7. 6×10^{-5}
Visible	4×10^{14}–7. 5×10^{14}	7. 6×10^{-5}–4×10^{-5}
Ultra violet	7. 5×10^{14}–3×10^{18}	4×10^{-5}–10^{-8}
X-rays	3×10^{16}–3×10^{20}	10^{-8}–10^{-10}
Gamma rays	3×10^{19}–3×10^{22}	10^{-9}–10^{-12}
Cosmic rays	3×10^{21}–	10^{-9}–

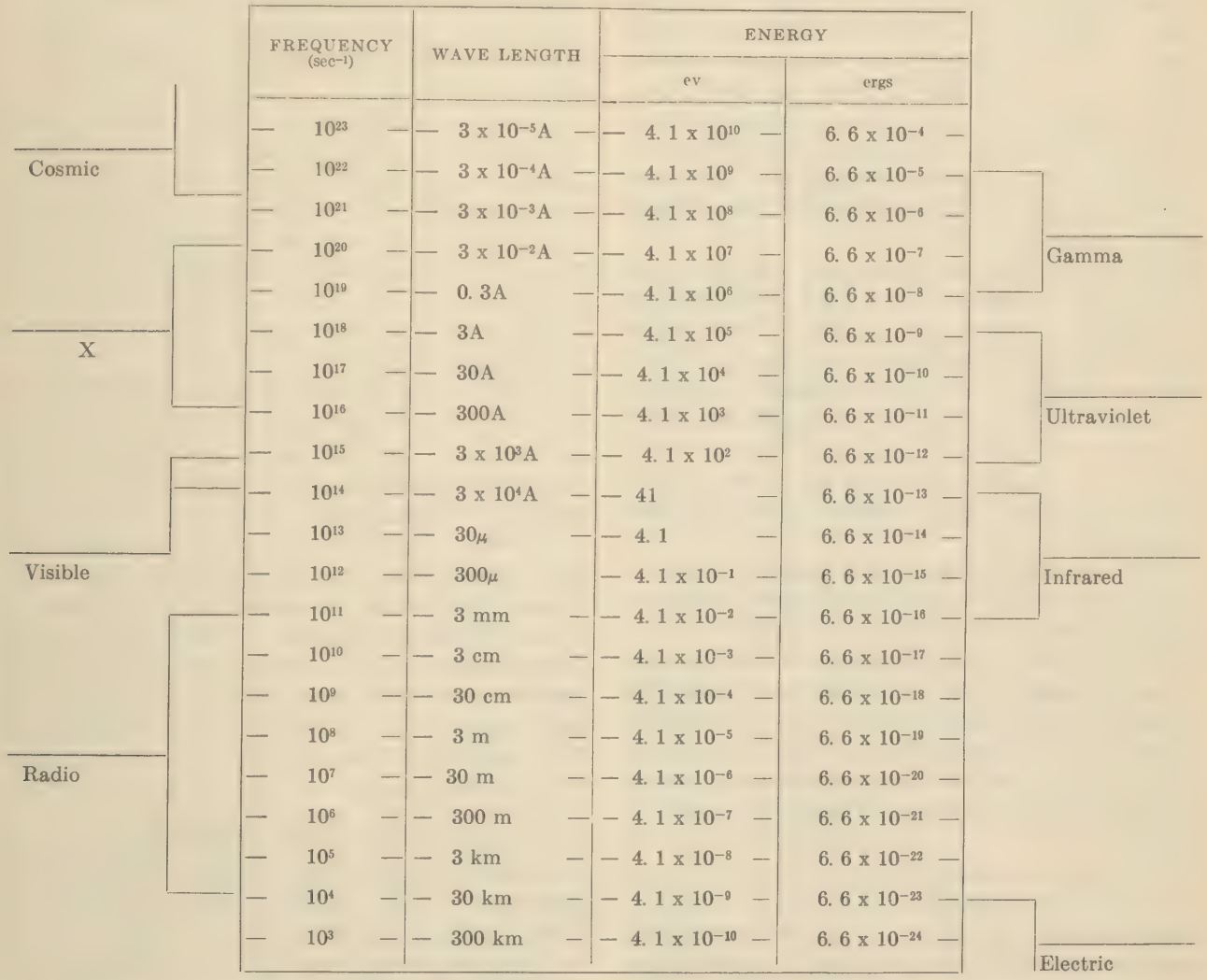

FIGURE 4–7.—The electromagnetic spectrum. Note the small portion occupied by the visible region even on a logarithmic plot.

same wavelength can be produced by X-ray methods. The properties of the radiations are identical and are independent of the method of production; only the frequency is important in determining the properties.

The electromagnetic spectrum is interesting and warrants a thorough study. A casual inspection reveals the enormous range of frequencies involved. Electric power lines radiate electromagnetic waves at the generator frequency, which is usually 60 cycles per second, but it would not be difficult to generate frequencies much lower than this. Thus, for all practical purposes, the lower frequency limit is zero. All frequencies are known, through the normal and ultra high frequency radio waves and the infra-red. It is somewhat startling to see how small a fraction is taken up by visible light. All sense of color and indeed all vision, is conveyed in a frequency range somewhat less than one octave. It is also interesting to note that the limits of the visible range as determined by the human eye are more sharply defined than any of the others.

The range of the electromagnetic spectrum is so great that several units are used in measuring wavelength. Wavelengths in the radio frequency region are commonly measured in meters. Visible light wavelengths are usually expressed in centimeters or in *Angstroms*, A (1 Angstrom$=10^{-8}$ cm.) or in microns, μ ($1\mu=10^{-4}$ cm.). The Angstrom is also used almost exclusively in measuring wavelengths in the X-ray and gamma ray region.

By the time visible light is reached, the frequency has already become nearly 10^{15} cycles per second but this is still low compared to the frequency of 10^{20} cycles per second associated with gamma or cosmic rays. It might seem that with improved techniques still higher frequencies might be observed. This may be true but it is probable that the upper limit is being approached, and it is certain that the upper limit does not extend to infinity.

Although the fundamental nature of all parts of the electromagnetic spectrum is identical, the methods of producing the various wavelenths vary tremendously. All wavelengths from infinity down to the infra-red can be produced by purely electrical means. It is possible to make oscillating circuits of a natural frequency so high that there is actually an overlap with the infra-red.

In most of the infra-red region, however, the frequencies are too high to be produced by oscillating electric circuits, and most infra-red radiation is obtained as radiation from hot bodies. Because of this, infra-red radiations are commonly known as heat waves or rays. This terminology is unsatisfactory since all radiation is eventually absorbed as heat. Infra-red waves are emitted from the rotations and the vibrations of the atoms making up the hot body.

As the temperature of the hot body is raised, visible light is emitted. Some of this radiation is produced by the same mechanism that emits infra-red. Some visible light is also produced by electron movements which will be described in detail in chapter 5.

When an electric arc is struck between metal electrodes, or when an electric current passes through a gas, visible, and ultraviolet frequencies are produced. The ultraviolet frequencies are due entirely to the electronic excitation resulting from the current. By increasing the energy of excitation, high ultraviolet frequencies can be produced, and some will overlap the upper limit of the X-ray region.

X-rays are produced by bombarding a heavy metal target with high speed electrons. The X-rays are produced by the rapid deceleration of the bombarding electron, or by the excitation of high energy electrons in the target. As the energy of the bombarding electrons is increased, the radiation frequencies increase and overlap into the gamma ray region. Gamma rays, which have an even shorter wavelength, are emitted from the nuclei of atoms. Much more will be said about gamma rays in chapter 6. Electromagnetic waves form only one component of cosmic radiation, and a discussion of this will be postponed to Ch. 7, sec. 7–15.

4.04 The Quantum Nature of Radiation

All of the components of the electromagnetic spectrum exhibit wave properties and can be refracted, diffracted, and show interference. These are necessary conditions for wave motions and it might seem that the whole story had been told. There are, however, other phenomena which can scarcely be explained on a wave basis. Examples

of such phenomena are the radiation from hot bodies (black body radiation), the production of X-rays, and the photoelectric effect (Ch. 5, sec. 5.10). The photoelectric effect will serve as an example of the inadequacy of the wave concept of radiant energy.

In the photoelectric effect a beam of light (infra-red, visible, ultra violet, etc.) falls on a metal surface, figure 4–8. The light may eject

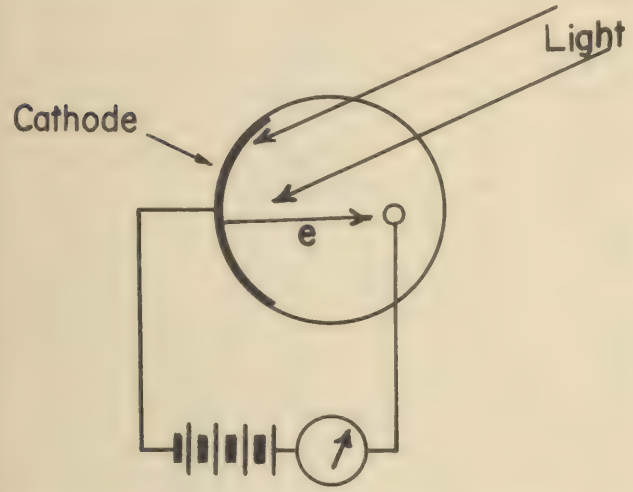

FIGURE 4-8.—The photoelectric effect. Electrons removed from the cathode surface by the incident light are attracted to the anode and constitute a current in the circuit.

electrons from the metal, and if this is in an evacuated bulb together with a positively charged collecting electrode, the electrons will be pulled over and a current will flow.

According to wave theory, the vibrations of the incoming electromagnetic waves set the electrons into vibration with increasing amplitude until they had acquired sufficient energy to break loose from the metal. It would seem then that a weak light would require more time to liberate an electron than a strong light, and there might be a light wave so weak that the electrons could never attain the energy necessary for escape. Such a prediction is at complete variance with the facts.

It is observed that the color or frequency of the light plays a very important role in producing photoelectrons. Thus the most intense beam of red light (low frequency) will not yield a single photoelectron from most metals, while the feeblest blue light (high frequency) will instantly produce a few. This suggested to Einstein, following some earlier work by Planck, that radiation is not a smooth, continuous flow of energy as pictured by the wave theory, but is rather a series of discontinuous packages of energy. The energy in each package, which is known as a *photon* or *quantum*, increases with the frequency of the light, being given by

$$E=h\nu \tag{3}$$

where $h=6.6\times10^{-27}$ erg-sec is Planck's constant and E the energy of the quantum in ergs.

A photon is apparently indivisible, and either exists or disappears completely upon giving up its energy in some process such as the photoelectric effect. The energy relations in the photoelectric effect will be given by the Einstein Equation,

$$h\nu=\phi+\frac{1}{2}m\nu^2 \tag{4}$$

The left-hand side of this equation is the energy available in the incoming photon. ϕ is the energy required to remove an electron from the surface of the metal, known as the work function. If the photon has an energy greater than ϕ, the electron will be ejected with a kinetic energy given by the last term in Eq. (4).

This immediately explains the photoelectric behaviour of light of different frequency. Red light has a low frequency and the associated quantum energy, by Eq. (3), may be less than ϕ, and hence no amount will liberate an electron. Blue light has a higher frequency, and the associated quantum energy may be larger than ϕ and hence sufficient to produce a photoelectric current. A series of experiments by Millikan completely verified the predictions of Eq. (4) and there can be no doubt that here radiation is behaving like a discontinuous series of energy packages.

Furthermore, a reverse application of Eq. (4) quantitatively explains the production of X-rays. Here the incident electron has a kinetic energy $\frac{1}{2}m\nu^2$ and can produce no radiation of frequency greater than that given by

$$\frac{1}{2}m\nu^2=h\nu \tag{5}$$

In this case the work function ϕ is so small compared to $\frac{1}{2}m\nu^2$ that it is neglected. This relation has also been completely verified by experiment.

A little reflection on Eqs. (4) and (5) will show that a sort of double-talk is involved. Radiation

is pictured as discontinuous and composed of photons of discrete energy, while at the same time the concept of frequency and wavelength is retained. This may be disconcerting and many people have spent much time and effort in trying to decide whether radiation is a quantum or a wave phenomenon. Actually it is necessary to assume a dual nature. Radiation may consist of some as yet unknown phenomenon which has some wave and some quantum characteristics. In its propagation through space and its transmission through non-absorbing media it behaves like a wave motion. In interactions with matter where energy exchanges are involved, the quantum nature predominates. The quantum behaviour becomes more pronounced at high frequencies and since radiological safety is primarily concerned with X-rays and gamma rays it is important to understand the quantum nature of radiation.

The first application of quantum ideas was made by Planck in 1901, to the problem of the radiation emitted by hot bodies. Physicists had developed the idealized concept of a black body, which is capable of emitting and absorbing radiations of all frequencies. This ideal is approached by an enclosed furnace with a small opening through which the interior radiations may be observed. Many measurements had been made of the amounts of energy radiated at various frequencies. Figure 4–9 shows the experimental results. At each temperature there is a frequency at which maximum energy is radiated. The frequency of this maximum increases with temperature according to Wien's displacement law which is usually written in terms of wavelength rather than frequency:

$$\lambda_M T = \text{Constant} \qquad (6)$$

λ_M = wavelength of maximum energy λ_M emission.

T = absolute temperature.

Constant = 0.29 cm. degrees.

This is a very useful relation since by its use the temperature of inaccesible hot bodies may be determined. For example the maximum energy of the sun is emitted at a wave length of about 4.5×10^{-5} cm. (green light) which corresponds to a temperature of about 6,000° C.

In the same way measurements of the energy radiated from the detonation of an atomic bomb

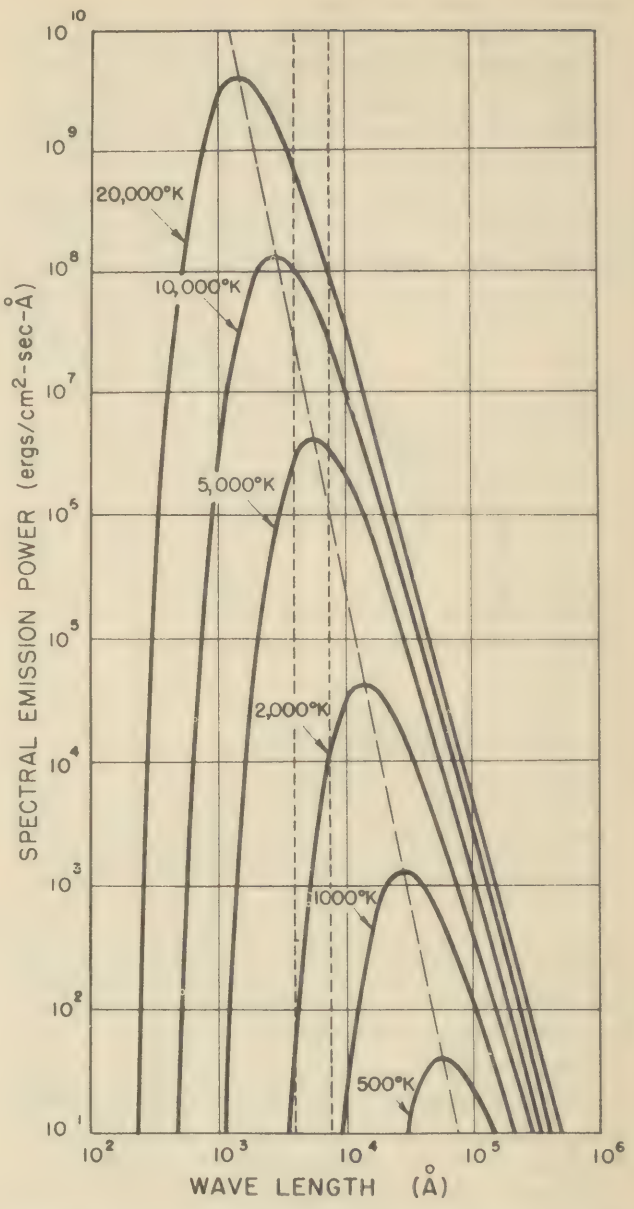

FIGURE 4–9.—The observed energy distribution of black body radiation as a function of temperature.

can be used to determine the temperature. If the maximum temperature reached in an atomic bomb explosion is 1,000,000° C., then λ_M will lie in the X-ray region. Therefore X-ray wave lengths will be emitted simply as temperature radiation, as distinct from the gamma and X-rays from nuclear disintegrations.

Many attempts had been made to explain the shape of the observed emission curves assuming

radiation to be a continuous wave motion, but all of these efforts yielded curves that were too high at the high frequencies. When Planck introduced the idea of radiation quanta, the difficulties disappeared, and the predicted curves agreed in all details with those experimentally observed. This is another example of the dual nature of radiation, and it should be noted that the original theories failed at the high frequencies where the quantum characteristics become more pronounced.

Before leaving the discussion of black body radiation it should be pointed out that the curves of Figure 4–9 represent the total energy radiated at each wave-length. The size of each emitted quantum increases steadily as the wave-length decreases in accordance with (Eq. 3), but the energy emitted is of course equal to the product of the number of quanta and the energy of a single quantum. At high frequencies the number of emitted photons is so low that the emission curves decrease as shown.

It is customary to measure radiant energy in ergs, but with the development of nuclear physics other units have been introduced. Thus, it is common to speak of a "50 kilovolt X-ray" or a "1 Mev gamma ray." This is really a specification of the energy of a single photon and not of the total energy of all photons in a beam.

Because of the enormous frequency range of the electromagnetic spectrum it is necessary to use a variety of instruments and methods of energy measurement. The methods used for the determination of X-rays and gamma rays will be discussed in Chapter 9. It might be pointed out in passing that the human eye is a remarkable instrument over its limited frequency range. It is most sensitive to green light having a wave-length of about 5.5×10^{-5} cm. and at this wave-length a sensation is obtained from about 10 photons or 3.6×10^{-11} ergs. The eye is able, moreover, to function satisfactorily at intensities 10^{10} times greater. This is an operating range not approached by any single man-made radiation measuring instrument. Even this tremendous range is unable to cope with the brilliance of the earliest phase of an atomic bomb detonation in air. At 10 miles this may have a brilliance 30 times as great as the sun and absorbing goggles must be worn to prevent eye injury.

Chapter 5

ATOMIC STRUCTURE

5.01 The Electrical Nature of Matter

It has already been demonstrated that electrons can be liberated from matter in a number of ways, e.g., by thermionic emission, by the photoelectric effect, and by other means. Regardless of the techniques employed to produce them, these electrons have the same properties. Exacting experiments have shown that these minute particles are identical. These negatively charged particles are therefore regarded as elementary constituents of matter. They are furthermore known to be fundamental particles, for no smaller unit of negative electricity has ever been observed.

The investigation of the conductivity of gases at low pressures has shown that in addition to electrons there are also positively charged particles which are much heavier than electrons. Their existence can be verified by using the equipment shown in figure 5–1. In the gas discharge tube,

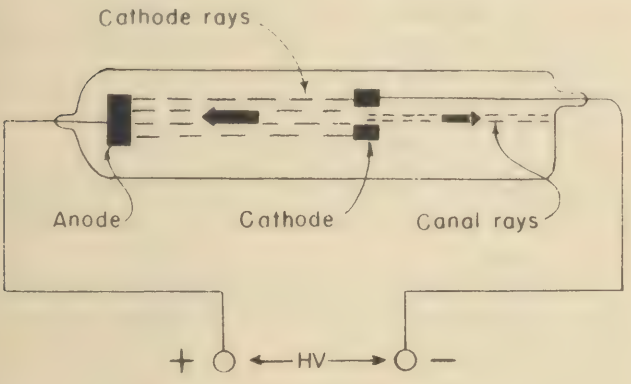

FIGURE 5–1.— Canal rays passing through a hole in the cathode of a cathode ray tube.

the electrons move toward the anode while the positively charged particles move toward the negatively charged cathode. If, as indicated, there is a small hole or "canal" in the cathode, these positive rays will fly through the aperture and impinge upon the end of the glass tube where they will cause fluorescence. By darkening the room, the path of the positive rays, sometimes called canal rays, is faintly visible in the space behind the cathode as a glow characteristic of the gas in the tube. Application of either a magnetic or electric field to the tube shows that the positive rays may be deflected from their otherwise straight trajectory.

Since the gas between the electrodes in figure 5–1 was non-conducting prior to the application of the high voltage to the terminals of the tube, it is clear that the gas was electrically neutral. When the high voltage source is connected to the terminals, the gas is made conductive and is said to be ionized. It is reasonable to assume that neutral particles of the gas are subject to separation into positively and negatively charged components which are then accelerated in opposite directions by the electric field, thus forming the canal rays and cathode rays.

In the case of hydrogen gas, which has the lowest molecular weight of any element, it has been found that the hydrogen molecule (H_2) breaks up into two positively charged particles, (H^+), which are called *protons*. The magnetic and electric deflection of the protons gives a measurement of their mass. Actually the ratio of charge to mass is measured, but this is equivalent to a mass measurement since the charge can be measured by other means. The proton has a mass 1.661×10^{-24} gm. and a charge of $1\,60 \times 10^{-19}$ coulombs. Its charge is opposite in sign to that of the electron but is identical in magnitude. The electron, with a mass of 8.98×10^{-28} gm., weighs only 1/1840th as much as the proton.

Although many exhaustive experiments have been carried out with hydrogen, no more than one electron is ever found associated with a single proton. This evidence proves that the hydrogen atom contains only one electron. As a result of this discussion, it is clear that the breaking up of the simplest atom into its components results in two electrically charged particles (H^+ ion, or proton, and e^-, or electron). This is the basis for the following discussion of the atomic structure of hydrogen.

5.02 The Hydrogen Atom and Other Elements

It is now known that this simplest of all atoms consists of a central heavy core (the proton) and a single outer electron. Lord Rutherford first

showed that the atom consists of a compact core or nucleus which is small in diameter as compared with the whole atom. Actually the hydrogen atom has a diameter of about 10^{-8} cms. (1 Angstrom unit), while the nucleus (proton) is only about 3×10^{-13} cms. in diameter. Thus the proton and electron are separated by relatively vast distances. The clue to the mystery of this empty atom occupied only by a minute nucleus and a still smaller electron is found in the nature of the electric field which exists inside the atom. A discussion of this subject is given in section 5.06.

Until relatively recently it was thought that helium was the next heaviest atom after hydrogen. However, Dr. Urey and his collaborators discovered a rare form of hydrogen which was twice as heavy as ordinary hydrogen. Since it was discovered in the form of water, the discoverers called this heavy water. Ordinary water has the chemical formula H_2O, whereas heavy water is often written as D_2O, indicating that the heavy water molecule is made up of one oxygen atom and two heavy hydrogen atoms, the symbol D standing for *deuterium* which is the technical name given to heavy hydrogen. The deuterium atom is chemically identical with the hydrogen atom.

Since the H-atom is composed of one proton and one electron, it might be logical to assume that the D-atom, which is twice as heavy, would be made up of two protons and two electrons. However, it is known experimentally that the deuterium atom contains only 1 electron and 1 proton. Furthermore, the exact weight of the deuterium atom is not the same as that which would result if two protons were in its nucleus. This dilemma perplexed the physicist for a long time until the discovery of a neutral particle of almost the same mass as the proton. When this new particle—the *neutron*—was discovered it was the key to the riddle of the structure of deuterium, as well as to that of all other elements.

Prior to the discovery of the neutron, physicists conceived of the deuterium nucleus as being made up of 2 protons and 1 electron; the electron inside the nucleus was postulated in order to leave a single positive charge on the nucleus, for the negative electron would neutralize the charge of one of the protons. However, conclusive evidence showed that it is not possible for electrons to exist within the nucleus. In spite of this fact, some recent books persist in using the term "nuclear electrons."

With the discovery of the neutron, the deuterium atom was assumed to consist of a nucleus of 1 neutron and 1 proton. This assumption has been justified by the corrections of the results predicted for many nuclear experiments. These two elementary particles can be used to build up the nuclei of all heavier elements, such as helium, lithium, beryllium, iron, lead, and uranium.

5.03 Atomic Nomenclature

Before proceeding to a discussion of the heavier elements, it will greatly simplify the discussion to introduce a consistent set of definitions and symbols. The following symbols will be used in this manual:

Z=*atomic number*. The number of protons in the nucleus of an atom. This atom carries Z elementary positive charges in the nucleus and Z electrons outside the nucleus.

A=*mass number*. The sum of all neutrons and protons in the nucleus of an atom.

N=*neutron number*. The number of neutrons contained in the nucleus of an atom.

n=the symbol for the neutron.

p=the symbol for the proton.

e=the symbol for the electron.

Nucleon=a word coined to refer to either nuclear constituent, the neutron or the proton.

Isotopes=two nuclei having the same number of protons but different numbers of neutrons.

In writing the formula for any isotope, the following form will be followed:

(Symbol of element)^A or $_Z$(symbol of element)^A

Thus for normal hydrogen; the form would be $_1H^1$, for heavy hydrogen the form would be $_1H^2$ or $_1D^2$, for normal helium the form would be $_2He^4$, for uranium 235 the form would be $_{92}U^{235}$. Strictly speaking it is not necessary to include the subscript since its value is fixed when the name of the element is given. It will be used frequently since it is convenient for balancing nuclear transformation equations.

PERIODIC ARRANGEMENT OF THE ELEMENTS

Series	Period	ZERO GROUP	GROUP I R_2O	GROUP II RO	GROUP III R_2O_3	GROUP IV RH_4 RO_2	GROUP V RH_3 R_2O_5	GROUP VI RH_2 RO_3	GROUP VII RH R_2O_7	GROUP VIII		
0												
1			HYDROGEN H 1.0078 No. 1									
2	1	HELIUM He. = 4.002 No. 2	LITHIUM Li = 6.940 No. 3	BERYLLIUM Be. = 9.02 No. 4	BORON B = 10.82 No. 5	CARBON C = 12.00 No. 6	NITROGEN N = 14.008 No. 7	OXYGEN O = 16.000 No. 8	FLUORINE F = 19.00 No. 9			
3	2	NEON Ne. = 20.183 No. 10	SODIUM Na = 22.997 No. 11	MAGNESIUM Mg. = 24.32 No. 12	ALUMINUM Al = 26.97 No. 13	SILICON Si = 28.06 No. 14	PHOSPHORUS P = 31.02 No. 15	SULFUR S = 32.06 No. 16	CHLORINE Cl = 35.457 No. 17			
4	3	ARGON A. = 39.944 No. 18	POTASSIUM K = 39.10 No. 19	CALCIUM Ca. = 40.08 No. 20	SCANDIUM Sc. = 45.10 No. 21	TITANIUM Ti = 47.90 No. 22	VANADIUM V = 50.95 No. 23	CHROMIUM Cr = 52.01 No. 24	MANGANESE Mn = 54.93 No. 25	IRON Fe = 55.84 No. 26	COBALT Co = 58.94 No. 27	NICKEL Ni = 58.69 No. 28
5			COPPER Cu. = 63.57 No. 29	ZINC Zn. = 65.38 No. 30	GALLIUM Ga = 69.72 No. 31	GERMANIUM Ge. = 7260 No. 32	ARSENIC As = 74.93 No. 33	SELENIUM Se = 79.2 No. 34	BROMINE Br = 79.916 No. 35			
6	4	KRYPTON Kr. = 82.9 No. 36	RUBIDIUM Rb. = 85.44 No. 37	STRONTIUM Sr = 87.63 No. 38	YTTRIUM Y = 88.92 No. 39	ZIRCONIUM Zr. = 91.22 No. 40	COLUMBIUM Cb = 93.3 No. 41	MOLYBDENUM Mo. = 96.0 No. 42	MASURIUM Ma = ? No. 43	RUTHENIUM Ru = 101.7 No. 44	RHODIUM Rh 102.91 No. 45	PALLADIUM Pd = 106.7 No. 46
7			SILVER Ag. = 107.880 No. 47	CADMIUM Cd. = 112.41 No. 48	INDIUM In = 114.8 No. 49	TIN Sn. = 118.70 No. 50	ANTIMONY Sb = 121.76 No. 51	TELLURIUM Te = 127.5 No. 52	IODINE I = 126.932 No. 53			
8	5	XENON Xe. = 130.2 No. 54	CAESIUM Cs = 132.81 No. 55	BARIUM Ba. = 137.36 No. 56	LANTHANUM La = 138.90 No. 57	CERIUM Ce = 140.13 No. 58						
9												
10	6					HAFNIUM Hf = 178.6 No. 72	TANTALUM Ta. = 181.4 No. 73	TUNGSTEN W = 184.0 No. 74	RHENIUM Re. = 186.31 No. 75	OSMIUM Os. 190.8 No. 76	IRIDIUM Ir. = 193.1 No. 77	PLATINUM Pt. 195.23 No. 78
11			GOLD Au = 197.2 No. 79	MERCURY Hg = 200.61 No. 80	THALLIUM Tl = 204.39 No. 81	LEAD Pb = 207.22 No. 82	BISMUTH Bi. = 209.00 No. 83	POLONIUM Po. = 209.99 No. 84	ALABAMINE Am. = ? No. 85			
12	7	RADON Rn = 222 No. 86	VIRGINIUM Va ? No. 87	RADIUM Ra = 226.97 No. 88	ACTINIUM Ac = 227.02 No. 89	THORIUM Th = 232.12 No. 90	PROTOACTINIUM Pa = 231.03 No. 91	URANIUM U = 238.14 No. 92	No. 93			

ELEMENTS NOT CLASSIFIED IN THE TABLE ABOVE

PRASEODYMIUM Pr. = 140.92 No. 59
NEODYMIUM Nd. = 144.27 No. 60
ILLINIUM Il. = 146.(?) No. 61
SAMARIUM Sm. = 150.43 No. 62
EUROPIUM Eu. = 152.0 No. 63
GADOLINIUM Gd. = 157.3 No. 64
TERBIUM Tb. = 195.2 No. 65
DYSPROSIUM Dy. = 162.46 No. 66
HOLMIUM Ho. = 168.5 No. 67
ERBIUM Er. = 167.64 No. 68
THULIUM Tm. = 169.4 No. 69
YTTERBIUM Yb. = 173.5 No. 70
LUTECIUM Lu. = 175.0 No. 71

NEW ELEMENTS

NOTE: The following elements have been discovered in conjunction with the work of the Manhattan Project.

NEPTUNIUM, Np, At. No. 93, At. Wt. 239
PLUTONIUM, Pu, At. No. 94, At. Wt. 239
AMERICIUM, Am, At. No. 95
CURIUM, Cm, At. No. 96

FIGURE 5-2.—Periodic table of the elements.

5.04 The Periodic System

Among the many elements, there are certain ones which bear remarkable relationships to one another in their physical and chemical characteristics. For example, this relationship is particularly striking in the case of the alkaline earth metals, Be, Mg, Ca, Sr, Ba, and Ra, all of which have similar chemistry. All have the same chemical valence, are metallic, have low density, exhibit similar atomic spectra, and have similar physical characteristics.

Mendeleeff arranged the elements in a series of groups as shown in figure 5–2. Such an arrangement is known as a Periodic Table of Elements. Elements which are in the vertical groups are all chemically related to one another. In the table, the number following the chemical symbol for the element gives the atomic weight of the element and the lowest number in each box indicates the atomic number of the element.

Examination of any group in the Periodic Table reveals that the differences between the atomic numbers of the members of a group follow a pattern—8, 8, 18, 18, 32. The electrons in an atom determine its chemical characteristics, so this regularity suggests that there is a building-up pattern followed by the electrons in the elements. The building-up principle requires that the electrons group themselves in definite shells about the nucleus. Each shell is characterized by having an upper limit to the number of electrons which it can hold.

All matter can be thought of as composed of the three elementary constituents: neutrons, protons, and electrons. Differences in the number of protons in the nucleus result in different chemical elements, for there must be an equal number of electrons outside the nucleus to make the atom electrically neutral. It is now necessary to look at the problems of atomic structure more quantitatively and in particular to investigate the arrangement of electrons.

5.05 Atomic Spectra and Energy Levels

Every element emits a characteristic optical spectrum which can, in fact, be used as an analytical means of identifying the element. If, for example, some hydrogen gas is placed in a discharge tube and electrically excited so that visible radiation is emitted, this radiation can be dispersed by either a diffraction grating or a prism into a series of lines as shown in figure 5-3. The sum of all the series lines emitted by hydrogen is known as the atomic or line spectrum of hydrogen. It was found experimentally that the Balmer series of lines (fig. 5–3 (a)) has wavelengths (λ) which can be empirically expressed by the relation

$$1/\lambda = R\left(\frac{1}{2^2} - \frac{1}{M^2}\right) \text{ where } M = 3, 4, 5 \ldots \infty \quad (1)$$

The quantity $1/\lambda$ is usually written as τ and is called the wave number. It is simply the number of wave lengths in a centimeter. R is a constant equal to 109,677 cm^{-1} and is known as the *Rydberg constant.*

In addition to the Balmer series of hydrogen lines which is located in the visible region of the spectrum, there is found another series in the ultra violet region; this is called the Lyman series. It can also be represented by an empirical expression as follows:

$$\tau = R\left(\frac{1}{1^2} - \frac{1}{M^2}\right) \text{ where } M = 2, 3, 4, \ldots \infty \quad (2)$$

Empirically, the wave lengths and wave numbers corresponding to lines in the Balmer and Lyman series are known quite accurately and are listed in table I.

TABLE I.—*Balmer and Lyman series*

[Wave lengths and wave numbers]

Balmer series		*Lyman series*	
λ	τ	λ	τ
6562.2 A (H_α)	15,233 cm^{-1}	1215 A	82,258 cm^{-1}
4861.3	20,264	1026	97,482
4340.5	23,032	972	102,823
4101.7	24,373	950	105,290
SERIES LIMIT			
3646.0 A	27,419 cm^{-1}	911 A	109,677 cm^{-1}

By substituting $M=3$ in Eq. (1), the wave number of H_α is found to be 15,233 in agreement with the value listed in column 2 of table I.

Instead of using the empirical equations, a new type of scheme can be employed to illustrate a fundamental principle of atomic spectra. The wave numbers of the series limits given in table I have been plotted in figure 5–4, putting the Lyman series limit value of 109,677 cm^{-1} as the

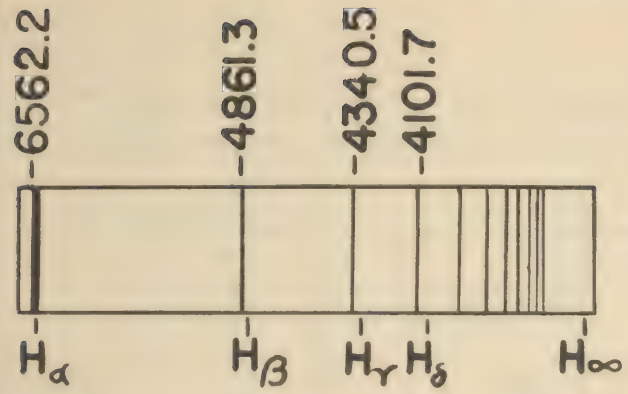

FIGURE 5–3a.—Emission spectrum of the hydrogen atom in the visible and near-ultraviolet region.

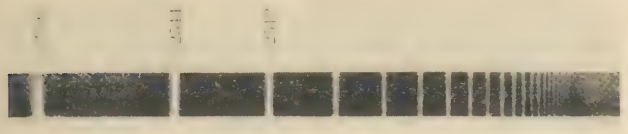

FIGURE 5–3b.—Absorption spectrum of the sodium atom. From *Atomic Spectra and Atomic Structure* by Gerhardt Herzberg, second revised edition, Dover Publications, Inc.

lowest line and the Balmer series limit as the next line. Similarly the series limits for successive series in the hydrogen spectrum (not previously mentioned) are located on succeeding lines in order of decreasing magnitude upward from the lowest level. It is seen that taking the difference between wave numbers corresponding to the level $M'=1$ and $M'=2$ yields $109{,}677-27{,}419=82{,}258$ the wave number of the first line in the Lyman series. It should be noted that the value of M' corresponds to the constants in the first term of Eqs. (1) and (2). This process has been diagramatically indicated in the drawing by vertical lines which are called transitions. In words, this principle can be stated as follows: There always exist for the spectrum of any atom, a series of wave numbers (term values), differences between which yield the wave number of the observed spectrum lines. This is known as the *Ritz Combination Law*, and tables used in connection with it (such as table I) are called term tables. This principle signifies that every atom has definite energy levels. Transitions within the atom from one energy level to another result in the emission or absorption of a spectrum line of a characteristic wave number determined by the difference between the energy levels.

Not all atoms emit a spectrum as simple as that of hydrogen, nor indeed is the hydrogen spectrum as simple as has been described. Figure 5–3 (b) shows a sodium absorption spectrum, each line of which is really a doublet instead of a single line. In general, the heavier elements emit correspondingly more complex spectra. Iron, for example, emits over 10,000 separate lines, all of which have been carefully measured and catalogued.

5.06 The Bohr Atom

The concept of the hydrogen atom as a proton and electron has already been introduced but no explanation was advanced to account for the stability of this system, nor for the emission of sharp and discrete spectrum lines from it. Between the proton and the electron there is an attractive force given by the equation

$$F=\frac{q_1 q_2}{r^2} \tag{3}$$

where in this case $q_1=q_2=e$. If the electron were at rest, it would be pulled into the proton by the Coulomb field. It must therefore be in a continuous state of motion. From classical electrodynamics an electron whirling about a proton would be accelerated. Since an accelerated electric charge should radiate energy, the electron would quickly spiral into the nucleus after producing a continuum of photons. Thus in the classical picture there was no explanation of the stability of the hydrogen atom or of the emission of discrete line spectra.

The Danish scientist, Niels Bohr first proposed a solution to this difficult problem by applying Planck's quantum hypothesis to an atomic system. As pointed out in section 4.04, Planck assumed that electromagnetic energy is emitted in quanta of energy E given by the relation

$$E=h\nu \tag{4}$$

where h, Planck's constant, $=6.65\times10^{-27}$ erg-sec. and ν is the frequency of the emitted electromagnetic radiation. Bohr saw the relation between

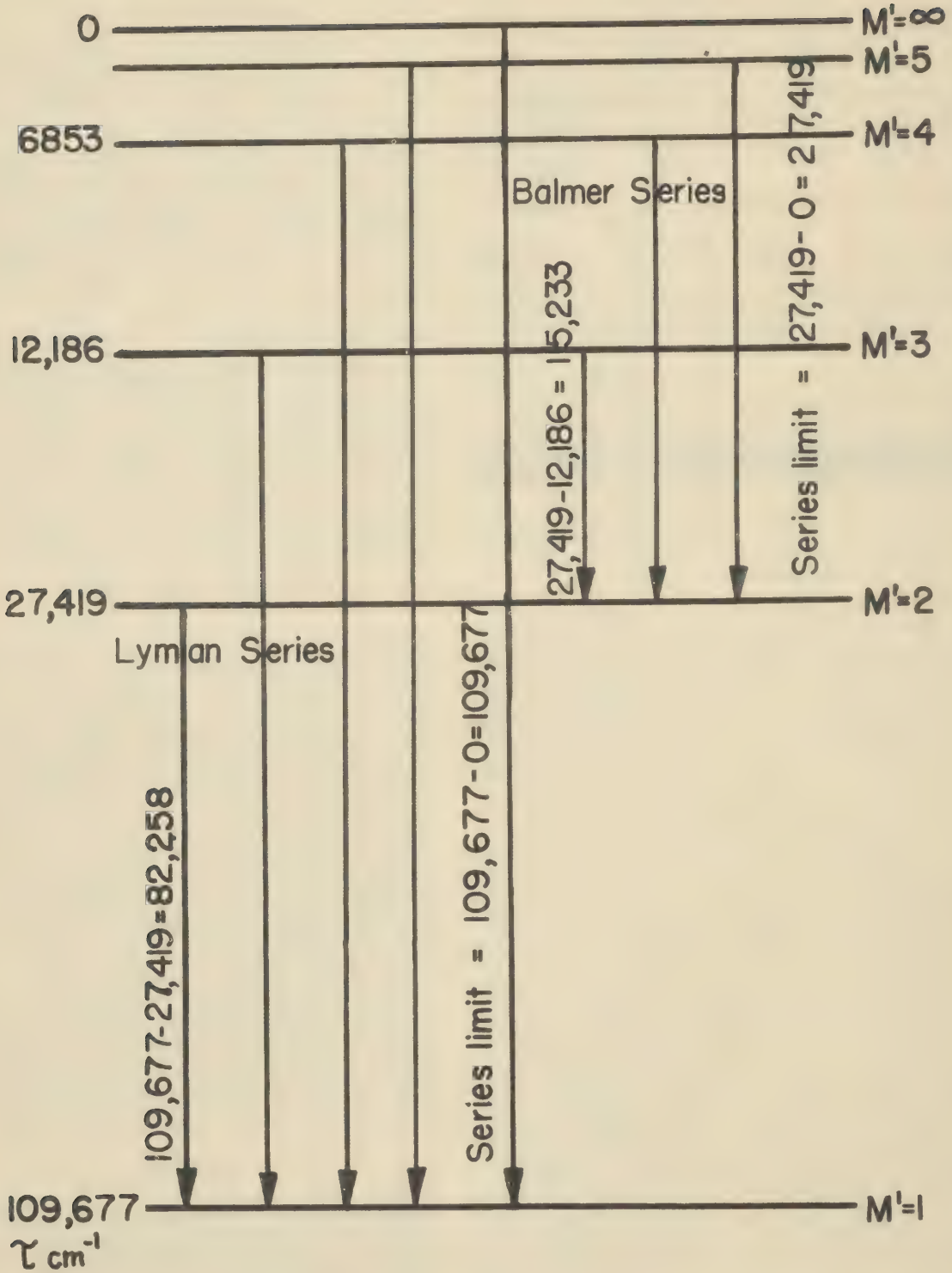

FIGURE 5–4.—Energy level diagram of hydrogen.

the Ritz Combination Principle and Planck's equation and proposed the relation

$$h\nu = E_2 - E_1 \tag{5}$$

where:

ν is the frequency of the emitted electromagnetic radiation.
E_2 is the initial energy of the atom (prior to emission).
E_1 is the final energy of the atom (after emission).

Recalling that $\lambda\nu = c$, where c is the velocity of light, this equation can be written:

$$\tau = 1/\lambda = E_2/hc - E_1/hc \tag{6}$$

From Eq. (6), it is clear that the values of a term in an atomic term table is equal to the energy of a state of an atom multiplied by the constant factor $1/hc$. Analytically the energy of an atomic state E_1 is given by the relation

$$E_1 = hc/\lambda \tag{7}$$

This is equivalent to stating that there exists, for every atom, discrete *stationary states*, each having a characteristic energy value. In addition, radiation is emitted from an atom whenever it jumps from one stationary state to another; this transition results in a radiation of wave number given by Eq. (6). It should be emphasized that while the atom is in a stationary state it does not radiate. This is contrary to classical theory.

According to the Bohr picture, the simple hydrogen atom should appear as in Figure 5–5. The electron revolves about the nucleus, which is assumed to be stationary, in discrete orbits corresponding to stationary states of the atom. Bohr further assumes that these stationary states are such that the momentum of the electron, mv, is restricted (quantized) to certain integral multiple values of $h/2\pi r$.

The first condition is fulfilled if the force required to accelerate the electron in its orbit (mv^2/r) is balanced by the electrostatic (Coulomb) force between the two particles. This yields

$$\frac{mv^2}{r} = \frac{e^2}{r^2} \tag{8}$$

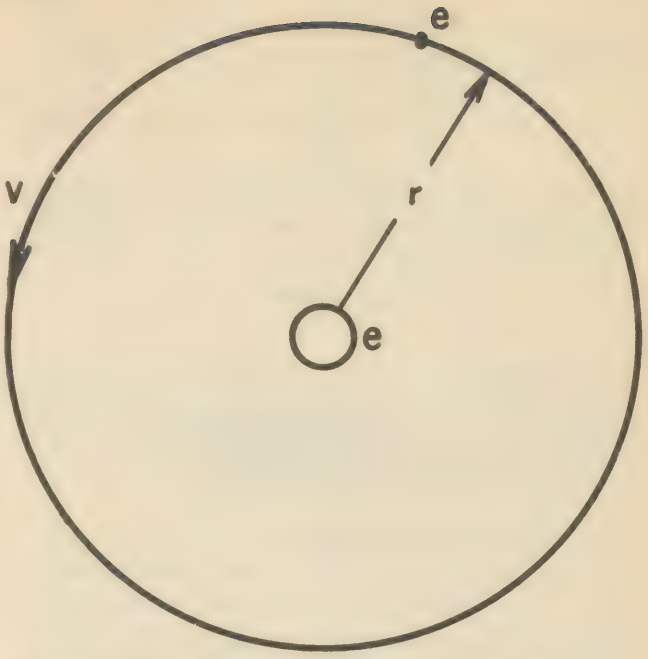

FIGURE 5–5.—Diagram of first orbit in the hydrogen atom.

The second condition may be stated as:

$$mvr = \frac{nh}{2\pi}$$

where:

$$n = 1, 2, 3, 4, \ldots \infty \tag{9}$$

Using these relations the total energy of an electron in one of its orbits can be calculated. This calculation is sketched as follows: The total energy of the electron equals its kinetic plus its potential energy

$$E = \frac{1}{2}mv^2 - \frac{e^2}{r} \tag{10}$$

Substituting from Eqs. (8) and (9)

$$E = \frac{-2\pi^2 me^4}{n^2h^2} \tag{11}$$

The fact that the energy is negative follows from the fact that the energy of the electron far removed from the atom (i. e. at infinity) is taken as zero. Since the force between the particles is attractive, work is done by the system in bringing the electron toward the atom, and the energy involved is negative. The energy will have a different value for each value of n which corresponds to a different electron orbit in the atom.

By Eq. (5), the frequency emitted by the transition of the electron from orbit 3 to orbit 2 is

$$\nu=\frac{E_3-E_2}{h}=\frac{2\pi^2me^4}{h^3}(1/2^2-1/3^2) \qquad (12)$$

It is seen that the above equation is exactly the same as Eq. (1) where $M=3$, if the Rydberg constant is taken as

$$R=\frac{2\pi^2me^4}{h^3} \qquad (13)$$

The value of R, obtained by substituting the constants in Eq. (11) is in excellent agreement with the experimental value and is a remarkable result of Bohr's theory.

5.07 Excitation and Ionization of Atoms

In the normal state, the electron in the hydrogen atom is in orbit 1 (i. e. $n=1$) or in the ground state. In order to raise this electron to higher orbits farther away from the nucleus, energy must be supplied to the system. This energy is normally supplied by means of collisions with other atoms or electrons. It is easy to calculate how much energy must be supplied to the H-atom to completely remove the electron from the atom. Such a process is known as ionization, and the resulting atom is ionized. It is equivalent to setting $n=\infty$ for the final state of the atom. Thus:

$$E=\frac{2\pi^2me^4}{h^2}\left(\frac{1}{1^2}-\frac{1}{\infty^2}\right)=\frac{2\pi^2me^4}{h^2} \qquad (14)$$

$E=22\times10^{-12}$ ergs or 13.5 electron volts

using $m=9\times10^{-28}$ *gm*, $e=4.8\times10^{-10}$ e.s.u. and $h=6.6\times10^{-27}$ erg-sec.

The energy required to remove the electron from the H-atom can be measured and checks very closely with this calculated value. The potential necessary to ionize any atom is known as the *ionization potential.*

The experiment to determine the value of the ionization potential in hydrogen consists of shooting a beam of electrons of known energy (voltage) into a tube of hydrogen gas at low pressure. If the energy of the bombarding electrons is high enough, it will cause the characteristic spectrum lines to be emitted from the gas, and these can be observed with a spectroscope. As the energy of the beam is dropped below 13.5 e.v., ionization ceases, but inelastic collisions between the incident electrons and hydrogen atoms occur and give rise to excitations of different series, and indeed, different lines in these series. Potentials necessary to cause emission of a characteristic line in, say, the Lyman series are called excitation potentials for those lines.

Atomic spectra can be excited in many ways other than in a gaseous discharge tube. Commonly used techniques are the carbon arc, the electric spark, and the hot flame.

In the heavier elements, it can be shown that the emission of ultra-violet, visible, and infra-red radiation is the result of transitions which occur on the part of the outermost electrons. Such radiations are completely independent of the inner electrons.

As the energy which is inelastically imparted to an atom increases, it is obvious from the relation $E=h\nu=\frac{hc}{\lambda}$ that the wave length of the most energetic radiation which can be emitted decreases. Thus if E is very small, the wave lengths which can be excited may be in the far infra-red. Then as E increases, the wave length decreases, passing through the visible region and down into the ultra-violet. Through the use of special techniques, atomic spectral lines as short as 100 Angstroms can be observed. Radiations much shorter than 100 A are usually known as X-rays and are characteristically produced in special vacuum tubes with which everyone is familiar. Because the study of these rays yields much information about the inner arrangement of the electrons of the atom as well as a wealth of other data, they will be discussed in detail.

5.08 X-Rays

The German physicist, Roentgen, discovered X-rays in the year 1895 while working with a high voltage gaseous discharge tube. The penetrating rays which he named "X-rays" are often referred to as Roentgen rays. Figure 5–6 shows a modern-type tube which is used to produce these rays. It is merely a high vacuum tube containing a heated filament, and a target, and as such is simply a diode across which is applied a high voltage. Electrons which are emitted from the heated cathode are accelerated toward the target, which they strike

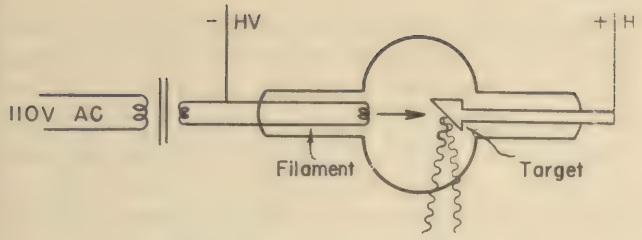

FIGURE 5–6.—Sketch of X-ray tube.

with a high velocity. This velocity, v, can be calculated by equating the kinetic energy of the electrons to the work done on the electrons by the electric field, in accelerating them across a potential difference of V volts. This work is given by the product e times V and thus:

$$\tfrac{1}{2}mv^2=eV \qquad (15)$$

When the electron strikes the target, which is usually made of a heavy metal, such as copper or tungsten, part of its energy is lost in the form of heat and part goes into producing X-rays. If all of an electron's energy goes into X-radiation, the wave length of this radiation is given by substituting the expression eV for E in the equation $E=hc/\lambda$; thus:

$$\lambda=\frac{hc}{eV} \qquad (16)$$

From this expression, it is clear that as the potential V across the tube is increased, the wave length of the emitted radiation decreases. Since it is experimentally known that the shorter the wave length of the X-rays, the greater is their penetrating power, it is obvious that as the potential V is increased, more penetrating (harder) radiation is produced. For example, let us calculate the shortest wave length emitted from an X-ray tube operating with $V=100{,}000$ volts. Substituting in Eq. (16) yields:

$$\lambda_{min.}=\frac{hc}{e\times\frac{50{,}000}{300}}=\frac{(6.6\times10^{-27})(3\times10^{10})}{(4.8\times10^{-10})(1.6\times10^{2})}$$

$$\lambda_{min.}=0.26\times10^{-8}\text{ cm. or }0.26\ A \qquad (17)$$

It is possible to devise an X-ray spectrometer, analogous to the spectrometer used in the optical region of the spectrum to split up the X-radiation coming from the target into its component wave lengths. Such a spectrum is shown in figure 5–7.

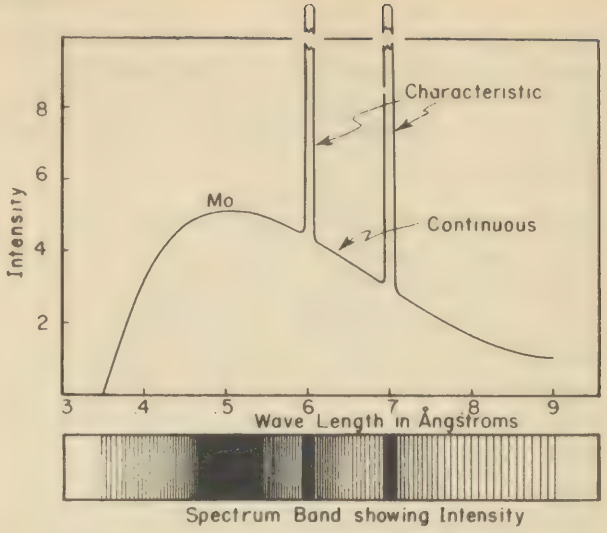

FIGURE 5–7.—Typical X-ray spectrum showing characteristic and continuous radiation. Spectrum taken with molybdenum target, 35 kv. across tube.

Two distinctly different types of X-rays appear in this spectrum:

a. Continuous or "white" X-rays which have a sharp lower wave length limit, rise to a maximum, and then taper off toward the longer wave lengths.

b. Characteristic or line X-rays which appear in the spectrum as sharp peaks superimposed on the continuous spectrum. These peaks or lines are uniquely characteristic of the element which is used as the target in the X-ray tube.

The most significant property of X-radiation is its high penetrating power. Almost everyone has at some time or other had an X-ray photograph made of his chest or some other part of his body and is thus familiar with the fact that X-rays can penetrate through many inches of human tissue. In X-raying the bones in the body a physician is able to record the shadow of the bones on a photographic plate because the bones, being composed of elements of higher atomic weight and being more dense than human tissue, absorb the radiation much more than does human flesh. X-rays produced by modern betatrons can penetrate many inches of solid lead, even though lead, in common with elements of high atomic number, is a much more efficient absorber for X-rays than is a lighter element.

X-rays can also cause fluorescence when they

strike certain materials which are particularly sensitive to this radiation. But far more important for the purpose of this discussion is the fact that X-rays act very efficiently to ionize gases through which they pass.

5.09 X-ray Spectra and Atomic Energy Levels

The continuous X-rays are produced by a mechanism which will not be discussed here, for it does not yield too great a contribution to our understanding of atomic structure. Instead, the mechanism of the production of the characteristic or line X-rays will be discussed, for it reveals very clearly much information that bears on atomic structure. The fact that each element yields a distinctly different line spectrum which is uniquely characteristic of the element, yet bears a similarity to the line X-ray spectra of other elements close to it in atomic number, suggests that these spectrum lines may be caused by electron transitions in the electron shells deep within the atom. Figure 5–8 shows a typical set of such

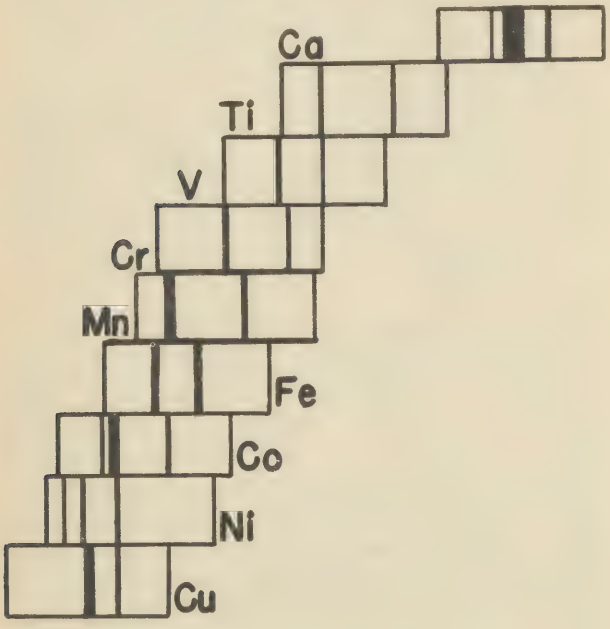

FIGURE 5–8.—Typical K series spectra.

spectra for the set of elements which lie on either side of iron in their atomic number. In this case, the shortest wave length X-ray line series have been illustrated. These are called the K-series lines. Longer wave length series are called L, M, N, etc.

Substantiating the assumption that the K-line X-rays arise from electron transitions deep within the atom, is the fact that the innermost electrons would be expected to be bound most strongly to the nucleus. If the K-line spectra of a series of contiguous elements are studied, it can be deduced (as was done by Moseley) that the wave number for any X-ray line can be analytically expressed as

$$\tau = R(Z-S)^2\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right) \tag{18}$$

Except for the factor $(Z-S)$ this equation is identical with the equation for the wave number of any line in the optical spectrum of hydrogen. In the expression, Z is the atomic number of the element, and S is a constant factor introduced to take acount of screening or reduction of the nuclear field due to electrons adjacent to and inside of the one undergoing a transition. If n_1 is taken equal to 1 and $n_2=2$ it is found that the expression

$$\tau = 3/4R(Z-S)^2$$

gives the wave number of the most intense (K_α) line for any element of atomic number Z. It can be shown that the staggering of the K_α lines (fig. 5–8) toward longer wave lengths with decreasing atomic number is completely explained by this expression. The latter is known as Moseley's law. In words, this law can be roughly stated as follows: X-ray line spectra for consecutive elements are similar to each other but are displaced relative to each other by a definite interval which increases regularly with decreasing atomic number. This law is more often written in the form.

$$\nu^{1/2} = K(Z-S) \tag{19}$$

where ν is frequency and K is a universal constant for all elements.

All of these results yield information about the structure of the atom but not of the nucleus of the atom. The physicist Kossel postulated that electrons arrange themselves in shells about the nucleus. These shells have definite limits to the number of electrons which can be placed in them and are illustrated for the mercury atom in figure 5–9. The mercury atom has $Z=80$, and therefore has to have 80 electrons arranged in shells about the positively charged nucleus in order

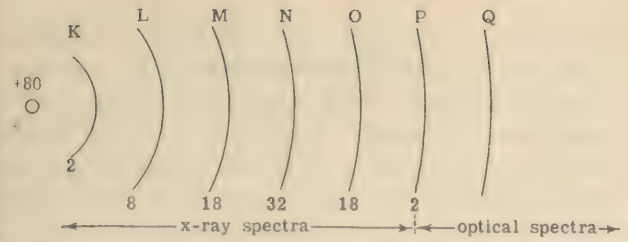

FIGURE 5–9.—Electronic structure of the mercury atom.

to be electrically neutral. These shells are built up as follows:

K shell has only 2 electrons and is closest to the nucleus, therefore these are the most tightly bound electrons in the mercury atom.

L shell has 8 electrons, called *L* electrons, which are not as tightly bound to the atom but yet require the input of more energy to the atom for their removal than do the electrons in the *M*, *N*, *O*, *P*, and *Q* shells. Similarly the *M*, *N*, and *O* shells are filled or saturated by 18, 32, and 18 electrons, respectively. The *K* shell corresponds to the shell with $n_1=1$ in Eq. (18). Just as optical spectral lines are produced in the mercury atom by, say, an electron falling into ring *P* from *Q*, or from still more remote orbits into the empty orbit *Q*, so also is an X-ray spectral line produced by an electron falling from shell *L* into the *K* shell. There must be a vacancy in the *K* shell since the *L* electron cannot possibly crowd into the *K* shell if 2 electrons are already there. In the production of X-ray line spectra, a *K* electron is ejected from its orbit by the collision of a high speed electron which is accelerated toward it with energy sufficient to remove it from its shell. Thereupon an *L* electron falls down to fill the vacancy in the *K* ring and the energy difference due to this transition from the *L* to *K* shell appears as a *K* X-ray line.

The *L* shell does not consist of just one energy level, but has in fact several levels, as do the *M*, *N*, and other shells. As seen in Figure 5–10, this accounts for the existence of three K_α lines.

5.10 Interaction of X-rays with Matter

It has already been stated that X-rays of long wave length are absorbed more strongly by an

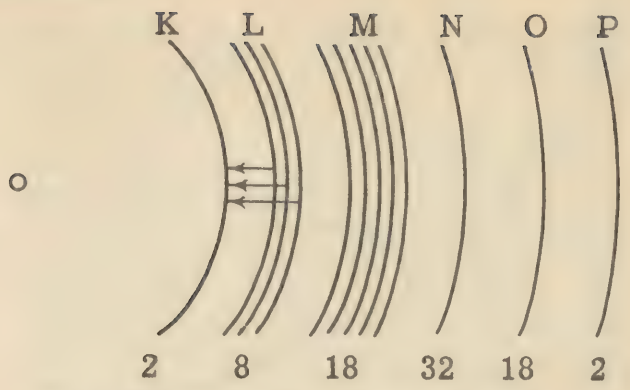

FIGURE 5–10.—Diagram of *L* and *M* shells.

element than similar rays of shorter wave length. As yet nothing has been said about the processes by which X-radiation is absorbed in matter. Experimentally it is known that a beam of X-rays is exponentially absorbed or reduced in intensity in traversing matter. For simplicity it is assumed that a beam of monochromatic X-rays, that is, X-rays of the same wave length, are incident upon a slab of absorbing material of a given

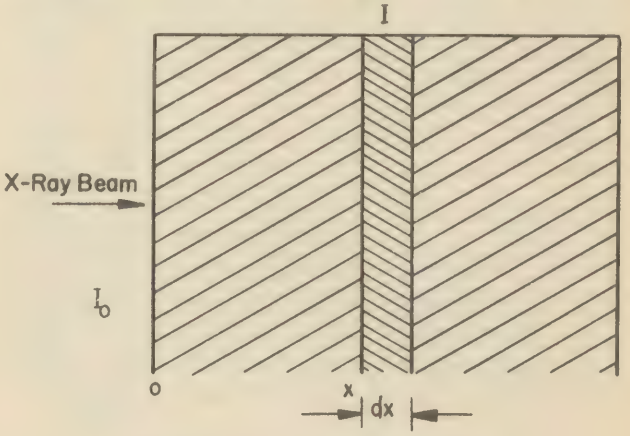

FIGURE 5–11.—X-ray absorption.

element. Let the initial intensity of the beam at the surface of the slab, where $x=0$, be I_0; then, as will be shown later, the intensity I at any distance x from the surface is given by

$$I=I_0e^{-\mu x} \tag{20}$$

where μ is called the linear absorption coefficient. Figure 5–12 illustrates how this relation appears when plotted on a linear scale. The symbol μ implies that there is a fractional decrease of intensity per unit thickness of absorber. This is significant, for it means that a certain fraction,

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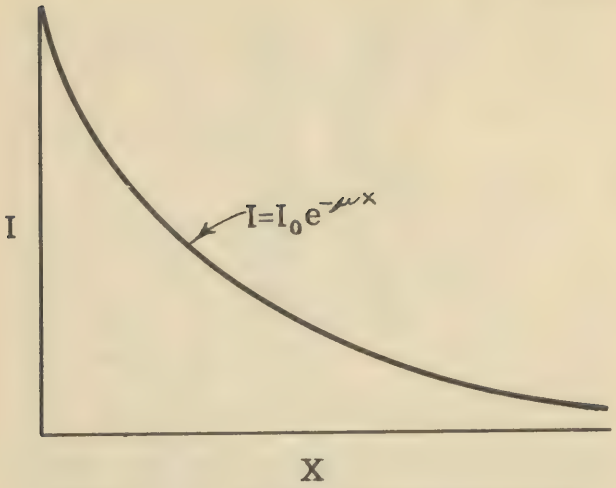


FIGURE 5–12.—Exponential absorption of X-rays.

albeit very small, will always penetrate through any finite thickness of absorber.

There are two general ways in which an X-ray can be caused to disappear from the X-ray beam. First, it can interact with an atom and have its energy transferred to another particle. Second, it can be scattered from the beam by elastic collisions with atoms. Specifically, three processes for X-ray absorption will be considered.

(*a*) *The photoelectric effect.*—When an X-ray quantum or photon collides with an atom, it may impinge upon an orbital electron and transfer all of its energy to this particle by ejecting it from the atom. If the incident photon carried more energy than that necessary to remove the orbital electron from the atom, it imparts to the electron its additional energy in the form of kinetic energy. This process is known as the photo-electric effect and obeys the Einstein photoelectric equation:

$$h\nu=\phi+\frac{1}{2}mv^2 \qquad (21)$$

Here, $h\nu$ represents the total energy of the incident photon; ϕ represents the energy required to remove the electron from its atom; and $\frac{1}{2}mv^2$ represents the kinetic energy of the ejected electron.

Electrons which have thus been ejected from atoms are called *photoelectrons*. These electrons are responsible for the ionization produced by X-rays. They may have considerable energy and cause ionization to occur in neighboring atoms. This effect is readily appreciated by observing the tracks which form in a Wilson Cloud Chamber when it is irradiated with X-rays. Each ion serves to form a nucleus for the condensation of a water drop upon it, for otherwise it could not be seen. (See Ch. 9, sec. 9.02 for details of the operation of a cloud chamber.) The ions created by the ejected photo-electrons form many separate zigzags in the chamber. A cloud chamber photograph of an X-ray beam is shown in figure 5–13. It will be observed that there are

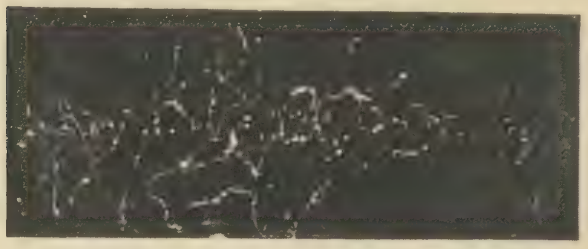


FIGURE 5–13.—X-ray photoelectrons seen in a cloud chamber.

Courtesy of The Royal Society

few very long tracks of these photoelectrons. This indicates that interactions which produce photoelectrons of high energy must be quite infrequent. From Eq. (21) it follows, then, that for X-rays of very short wave length the photoelectric effect will be less important.

It should be obvious that the ejection of a photoelectron leaves a gap in the electron shell, and this gap will be filled by an electron transition from a higher shell. Let it be assumed that a photoelectron is ejected from the K shell; then an L electron will jump to the K shell, emitting a K_α X-ray. This process leaves a gap in the L shell, and an M electron may make a transition to it and emit an L X-ray. Thus if a block of material, preferably a dense element, is placed in an X-ray beam, it will itself become a source of X-rays for the reasons just presented. This radiation is usually called characteristic or fluorescence radiation. The former name is given to it, since it is obvious that the radiation will be uniquely characteristic of the element in the radiated block. This secondary radiation is usually very homogeneous, that is, it consists of only a few sharply defined wave lengths.

(*b*) *The Compton Effect.*—For X-rays of shorter wave lengths, another process occurs. It is extremely important to the physicist, for it shows that X-ray photons behave as small particles and

undergo billiard-ball type collisions, even though a photon was formerly thought to have essentially wave characteristics. This process was first discovered by Arthur H. Compton and so is called the Compton Effect.

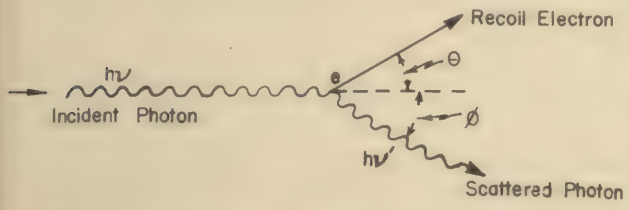


FIGURE 5-14.—Compton effect.

Suppose a photon of energy $h\nu$ collides with an electron e. As a result the incident photon is scattered at an angle ϕ away from its original direction, and the struck electron recoils in a direction at an angle θ to the trajectory of the primary photon. The incident photon can be treated as if it were a particle of mass given by the equation.

$$m=\frac{h\nu}{c^2} \qquad (22)$$

In table II are shown wave lengths and associated masses of several photons.

TABLE II.—*Masses of photons of different wave lengths*

λ Wave length	$h\nu$ Energy	m Mass	m/m_e Ratio of mass of photon to mass of electron	r
	ergs	*gms*		
10,000 A	2×10^{-12}	2×10^{-33}	2.4×10^{-6}	1.2 ev
100 A	2×10^{-10}	2×10^{-31}	2.4×10^{-4}	120 ev
10 A	2×10^{-9}	2×10^{-30}	2.4×10^{-3}	1,200 ev
1 A	2×10^{-8}	2×10^{-29}	2.4×10^{-2}	12 Kev
0.1 A	2×10^{-7}	2×10^{-28}	0.24	0.12 Mev
0.01 A	2×10^{-6}	2×10^{-27}	2.4	1.2 Mev

From this table it is seen that an infra-red photon corresponding to an energy of about 1 electron volt has a mass about a millionth that of an electron (the mass m_e is the mass of the electron). For a photon to have a mass equal to that of an electron at rest, it must be about 0.02 A in wave length or about 0.5 Mev in energy. Since the Compton process is important for photons of relatively high energy, say, 2 Mev, it is clear from the foregoing discussion that in a Compton collision, the photon is actually heavier than the electron at rest.

Application of the laws of conservation of energy and momentum to the Compton collision process allows an accurate calculation of the direction of the recoil electron and also it permits a calculation of the change in wave length of the scattered photon. Since the recoil electron (often called the *Compton electron*) takes energy from the incident photon, the wave length of the scattered photon must be longer than that of the incident one.

The calculations made on the assumptions stated in this section are accurately confirmed by experiment. If a beam of X-rays, all having the same wave length, is allowed to fall upon a block of an element, such as carbon, the X-rays are scattered by the outermost loosely bound carbon electrons. Close examination of the scattered radiation shows that some of the scattered rays are of longer wave length than those in the primary beam irradiating the carbon. Many photons scattered by the carbon electrons will not be changed in wave length. These rays are said to undergo pure scattering, in contrast to those which suffer *Compton scattering* and a change in wave length.

Pure scattering, considered on the basis of classical views, is explained by an electromagnetic interaction of the X-ray photons with electrons in the scattering element. The X-rays, acting as waves, excite the electrons to oscillation and these reemit the radiation with no change in frequency. Such radiation is scattered uniformly in all directions.

(*c*) *Pair production.*—In general, at still shorter wave lengths where neither of the two effects just discussed is appreciable, a new and rather startling phenomenon takes place.

Figure 5–15 is a rough sketch of the simple pair production process. A high energy photon in the vicinity of the nucleus may give rise to the creation of a pair of electrons. One of these electrons is of the ordinary type carrying a negative charge, but the other is a particle equal in mass to that of an electron but bearing a positive charge of $+e$. It is called a *positron* and is denoted by the symbol e^+. The symbol e^- or simply e refers to the ordinary negative electron. A term, the

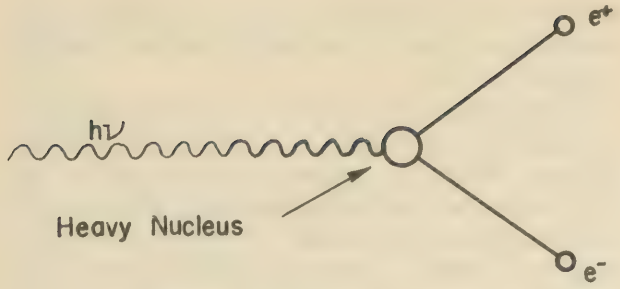


FIGURE 5–15.—Pair production.

negatron, may sometimes be found to refer to a negative electron, but it is not in common usage.

In the process of pair production, all of the photon energy is used up and goes into forming the electron pair and into imparting kinetic energy to this pair. Before a pair can be produced, the incident photon must have a minimum energy of 1 Mev. Usually a much higher energy is necessary, especially in the light elements. For example, in lead, photons of 3 Mev lose about 50 percent of the their energy in pair production, whereas in aluminum only a few percent of the energy is similarly expended.

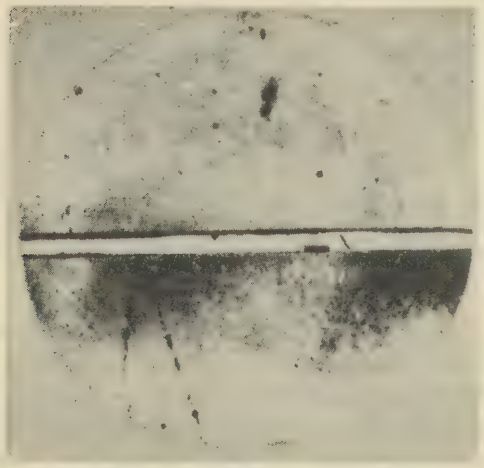


FIGURE 5–16.—Cloud chamber photograph of pair production.

The process of pair production is often referred to as the materialization of radiation. It is graphically illustrated in cloud chamber photographs such as the one shown in figure 5–16. Centered in the cloud chamber is a 1 cm. lead plate upon which a 5 Mev photon is incident. Note that the upper half of the plate is devoid of tracks since the 5 Mev photon is non-ionizing. As the photon strikes the lead plate, it disappears and creates a pair of electrons which diverge from their common point of origin.

It is interesting to note here that the positron finally undergoes a reaction which is the inverse of the pair production process. Just as the photon materialized into two particles, the positron is annihilated and gives rise to two photons of equal energy. These photons are called annihilation radiation.

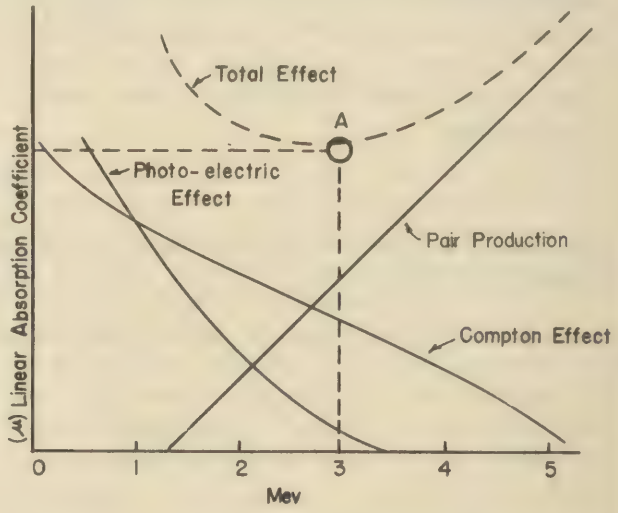


FIGURE 5–17.—Relative importance of photon absorption process in lead.

Figure 5–17 shows the relative significance of the three absorption processes for the element lead. It should be remembered that such a set of curves is valid for only one element, since each of the processes depend upon the atomic number of the absorbing element. An important point to note in figure 5–17 is that the total effect as shown by the dotted curve has a minimum absorption at 3 Mev. In other words, lead is most transparent to radiation of 3 Mev energy and is more opaque at both higher and lower energies. The minimum absorption for iron occurs at an energy of about 7 Mev.

5.11 The Roentgen.

Up to now, whenever X-radiation has been mentioned, its intensity has been given in terms of arbitrary units. It is convenient to define a standard unit for the measurement of the intensity of this radiation. The practical unit of X-ray quantity which has been adopted is called the *roentgen* and is denoted by the symbol *r*. *It is that amount of X-rays which will produce 1 electrostatic unit of ions in 1 cubic centimeter of air under standard conditions of temperature and pressure.* For a rigorous definition, it must also be required that, in making the measurement, certain complicating effects such as those due to secondary electrons and to the influence of the wall of the measuring instrument chamber be considered.

The unit of X-ray intensity is given in terms of 1 roentgen per unit time. There is frequently confusion as to the difference between quantity and intensity of X-radiation. Intensity is the quantity of X-radiation measured at any point per unit time. For example, an X-ray tube may give an intensity of 0.30 roentgens per second (*r*/sec) at a distance of 1 meter from the tube. But if one were to stand at this point for 10 minutes the total quantity or dose of X-rays received at that local point would be 180 roentgens, quite different from the intensity, or *dose rate* which would be 0.3 roentgens/sec. A dose of 180 *r*, if delivered over the entire human body, would result in serious consequences to the individual. For this reason, considerable research has been done to determine just how much (remember that this means quantity or roentgens), X-radiation can be accepted by a human per day for an indefinitely long period so that the individual may suffer no harmful effects. In Chapter 13 this problem will be discussed in greater detail.

Instruments used for measuring X-radiation will be discussed in chapter 9, and therefore no mention is made here of the practical means by which the Roentgen unit is measured.

5.12 Wave Mechanics

The evidence from both optical and X-ray spectra has been used in the foregoing sections to throw light upon the structure of the electronic shells which surround the nucleus. As a result of the quantum theory and of the Bohr model of the atom, the problem of atomic structure, at least so far as the orbital electrons are concerned, seems to be fairly well solved. It should be borne in mind that only a small fraction of the problem has been treated here and it must be accepted on faith that problems not treated are equally well susceptible to solution by the application of quantum-mechanical methods.

When the Bohr theory was applied to atoms more complex than simple hydrogen-like systems, grave difficulties arose which could not be resolved by then existing mathematical and analytical techniques. In fact, the next most complex atom, helium, presented an impasse to the theoretical physicists. The introduction of new theories, known as wave mechanics and matrix mechanics by Schroedinger and Heisenberg removed many of the objections present in the old quantum theory and yielded correct results when applied to the helium atom. The introduction of the quantum conditions in Bohr's theory was very arbitrary and subject to criticism. In the new wave mechanics, the quantum conditions are introduced naturally and today the validity of wave mechanical treatment of atomic systems is well substantiated.

The subject of wave mechanics is too involved for treatment in this text and would require an extensive mathematical background to follow even an elementary discussion of it. According to the principles of wave mechanics, every particle of mass m has associated with it a phase wave of wave length given by the De Broglie relation

$$\lambda = \frac{h}{mv} \tag{23}$$

where h is again Planck's constant and v is the velocity of the particle. This equation expresses the dual nature of matter. That is, it endows every particle with certain wave characteristics and thus resolves the difficulty which perplexed physicists for so long when they tried to determine whether light was wave-like or corpuscular. It is now known that light in common with other electromagnetic photons behaves both as a wave and as a particle, depending upon the conditions of the experiment. A proton moving with $\frac{1}{10}$

the velocity of light has, according to Eq. (23) an associated wave length of

$$\lambda = \frac{6.6\times10^{-27}}{(1.6\times10^{-24})(3\times10^{9})} = 1.4\times10^{-12} \text{ cm.}$$

That such protons actually exhibit wave properties corresponding to this short wave length is verified in diffraction experiments wherein a beam of protons is diffracted by a thin gold foil.

5.13 Mass Spectroscopy

Earlier in this chapter (see sec. 5.01) mention was made of the fact that positive ions could be deflected with appropriate electric and magnetic fields and thus they could be weighed. Instruments designed specifically for analyzing and weighing positive ions are known as mass spectrographs. A diagram of a Dempster type double-focusing mass spectrograph appears in figure 5–18. In figure 5–19 is shown the corresponding

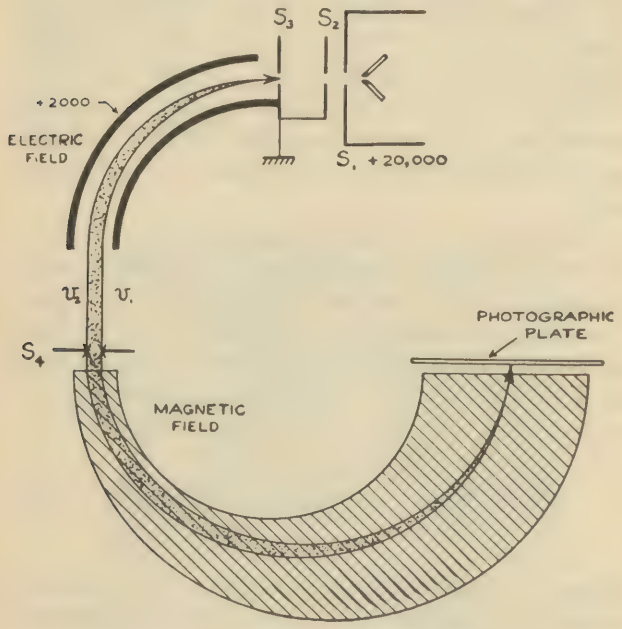


FIGURE 5–18.— Diagram of a Dempster type mass spectrograph.

spectrograph box. This box fits between the poles of a large electromagnet and connects to a vacuum system which maintains the box assembly at a pressure of less than 10^{-5} mm. Hg pressure.

Positive ions are produced by sparking together two electrodes in a vacuum. The ions thus generated are accelerated by a high voltage source of about 15,000 volts into a slit system which effectively collimates the ion beam. Upon entering slit S_3, the ions are bent by the 90° electric field of several thousand volts, whereupon they emerge from this field and pass through a defining slit S_4. At this point, all those ions of velocity v_1 come to a common focus; the faster ions of velocity v_2 come to a second common focus. There is, therefore, a velocity spectrum of ions over the breadth of this slit. As the ions enter the magnetic field they are bent through 180°, and all ions having the same e/m ratio (charge to mass), are focused at a common point on the photographic plate, where they produce an image. This latter type of focusing is known as direction focusing and is independent of the velocity of the ions.

Figure 5–20 is a reproduction of a typical mass spectrum taken with the instrument shown in the preceding figure. The spectrum shown was obtained from the impurities which were present in a sample of uranium which was being analyzed. Some of these elements were present to the extent of only 1 part in 1 million and yet they are readily identified in the plate. Since the instrument focuses all ions of the same e/m ratio, singly ionized atoms of mass 7 (lithium) fall at the same point on the plate as doubly ionized atoms of mass 14 (nitrogen). In fact the strong line between lithium and beryllium is due to doubly charged oxygen.

In 1913 Thomson used a mass spectrograph in establishing that the element neon had two separate components, one of mass 20 and one of mass 22. Prior to his discovery of neon 22, the fact that the atomic (chemical) weights of many elements differed widely from whole numbers had no reasonable explanation. Indeed, chlorine with an atomic weight of 35.46 diverged widely from the whole numbers 35 and 36. Thomson solved this vexing problem by assuming that each element may have atoms which have different mass but are chemically identical. Such atoms are called *isotopes*. From Thomson's assumption it follows that the chemical atomic weight is an average weight of the various isotopes of that element. Chlorine, for example, has been shown to have two isotopes, one, Cl^{35}, which is about three times more abundant than Cl^{37}, the other isotope. The weighted average of these isotopes yields an average atomic weight in good agreement with the measured weight.

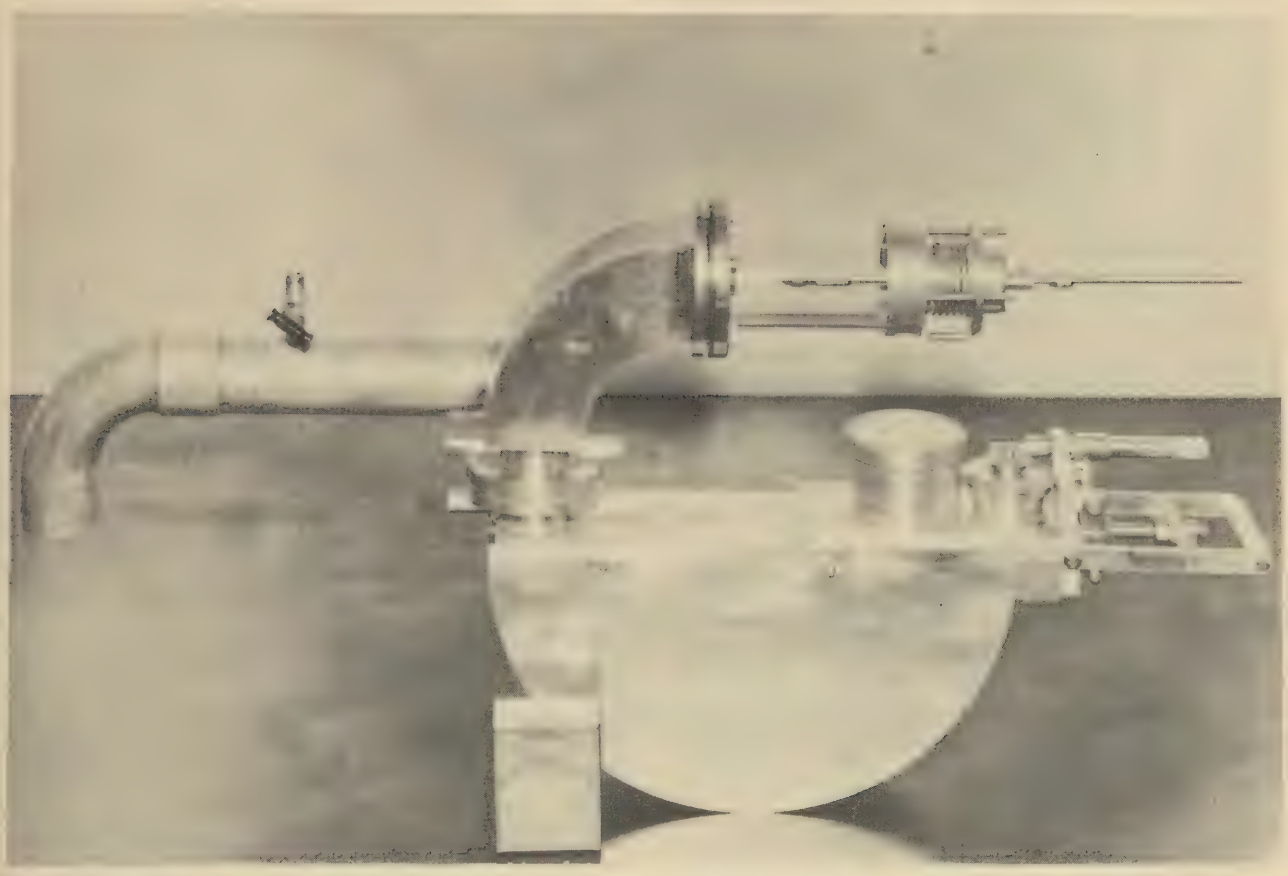
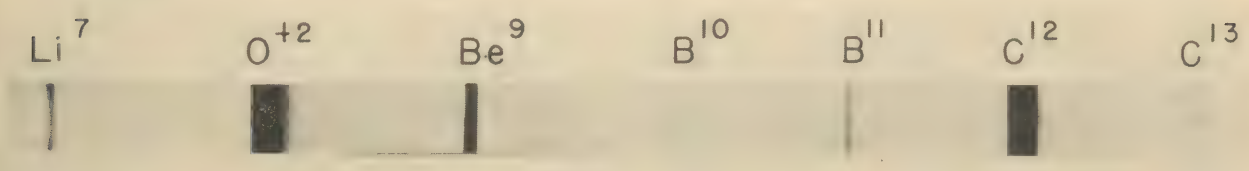
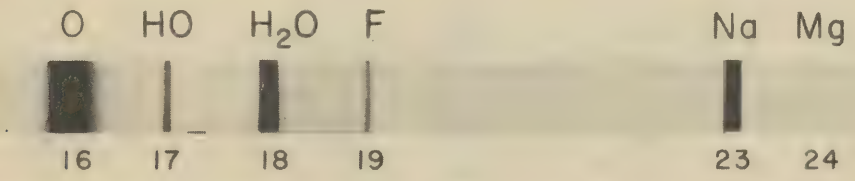


FIGURE 5–19.—Dempster type mass spectrograph. Auxiliary equipment (magnet, etc.) not shown.



(a) Light Element Impurities in Metal Sample



(b) Impurities in Metal Sample

FIGURE 5–20.—Typical mass spectra

From the discussion given earlier, it is clear that the Ne^{22} isotope which Thomson discovered differs from Ne^{20} in that its nucleus contains 2 more neutrons. As long as the number of protons in the nucleus remains the same, the presence of more neutrons in the nucleus does not change the chemical characteristics of the element.

5.14 Mass Spectra

In the case of optical and X-ray spectra, it was found that these spectra were invaluable in unraveling the mystery of the electron shell structure. It might therefore be expected that mass spectra will be of similar value in giving clues about the inner structure of the nucleus.

Every element has one or more isotopes. In some cases, it may have only one isotope—in such a case this particular isotope has a 100 percent abundance. Other elements, such as tin, may have as many as 10 isotopes with abundances varying from a small fraction of 1 percent to many percent. Figure 5–21 shows what is called an isotope pattern or sometimes isotope profile. It is simply an intensity plot of the isotope abundances listed in table III.

TABLE III.—*Relative abundance of naturally occurring tin isotopes*

Isotope No.:	*Percentage abundance*
112	1. 1
114	. 8
115	. 4
116	15. 5
117	9. 1
118	22. 5
119	9. 8
120	28. 5
122	5. 5
124	6. 8
	100

Certain regularities in the number of naturally occurring isotopes per element are manifest in the periodic chart shown in figure 5–22. For example, the odd groups contain elements having usually only a single or at most two isotopes, whereas the even groups rarely contain elements with single isotopes (per element) and more often each element has more than two isotopes. The significance of this isotope distribution among the elements will be discussed in chapter 6.

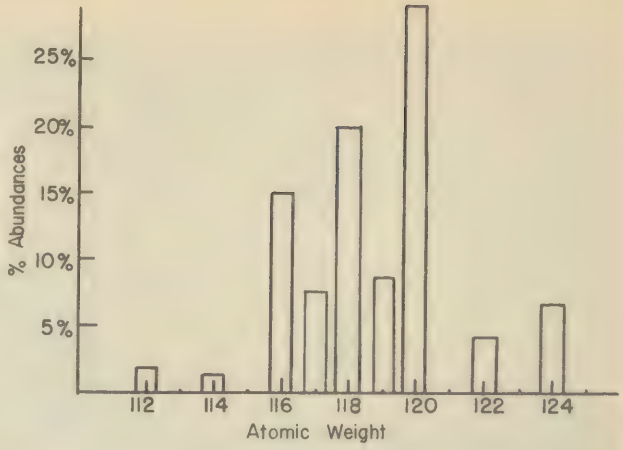


FIGURE 5–21.—Isotope pattern of tin.

With precision mass spectrographs at their disposal, physicists were able to determine accurately the atomic masses of the elements. The chemists had already selected oxygen as the standard element upon which their system of atomic weights was based; this choice was rather unfortunate, since oxygen has three isotopes. In comparing atomic weights, physicists use the most abundant isotope of oxygen as a standard in the physical atomic weight scale and take it equal to 16.00000. The masses of isotopes of other elements can be accurately measured with respect to O^{16}; some values so obtained are tabulated in table IV.

TABLE IV.—*Exact masses of various elements*

Element	Symbol	Z	Atomic weight = M (mass units)
Hydrogen	H^1	1	1. 008123
Deuterium	H^2 or D	1	2. 014745
Helium	He^4	2	4. 003905
Lithium	Li^7	3	7. 01657
Carbon	C^{12}	6	12. 00398
Nitrogen	N^{14}	7	14. 0073
Oxygen	O^{16}	8	16. 0000
	O^{18}	8	18. 0057
Fluorine	F^{19}	9	19. 0045
Neon	Ne^{20}	10	19. 9988
Calcium	Ca^{40}	20	39. 9738
Nickel	Ni^{60}	28	59. 94977
Tin	Sn^{120}	50	119. 93
Mercury	Hg^{200}	80	200. 028
Thorium	Th^{232}	90	232. 12
Uranium	U^{235}	92	235. 125
	U^{238}	92	238. 132

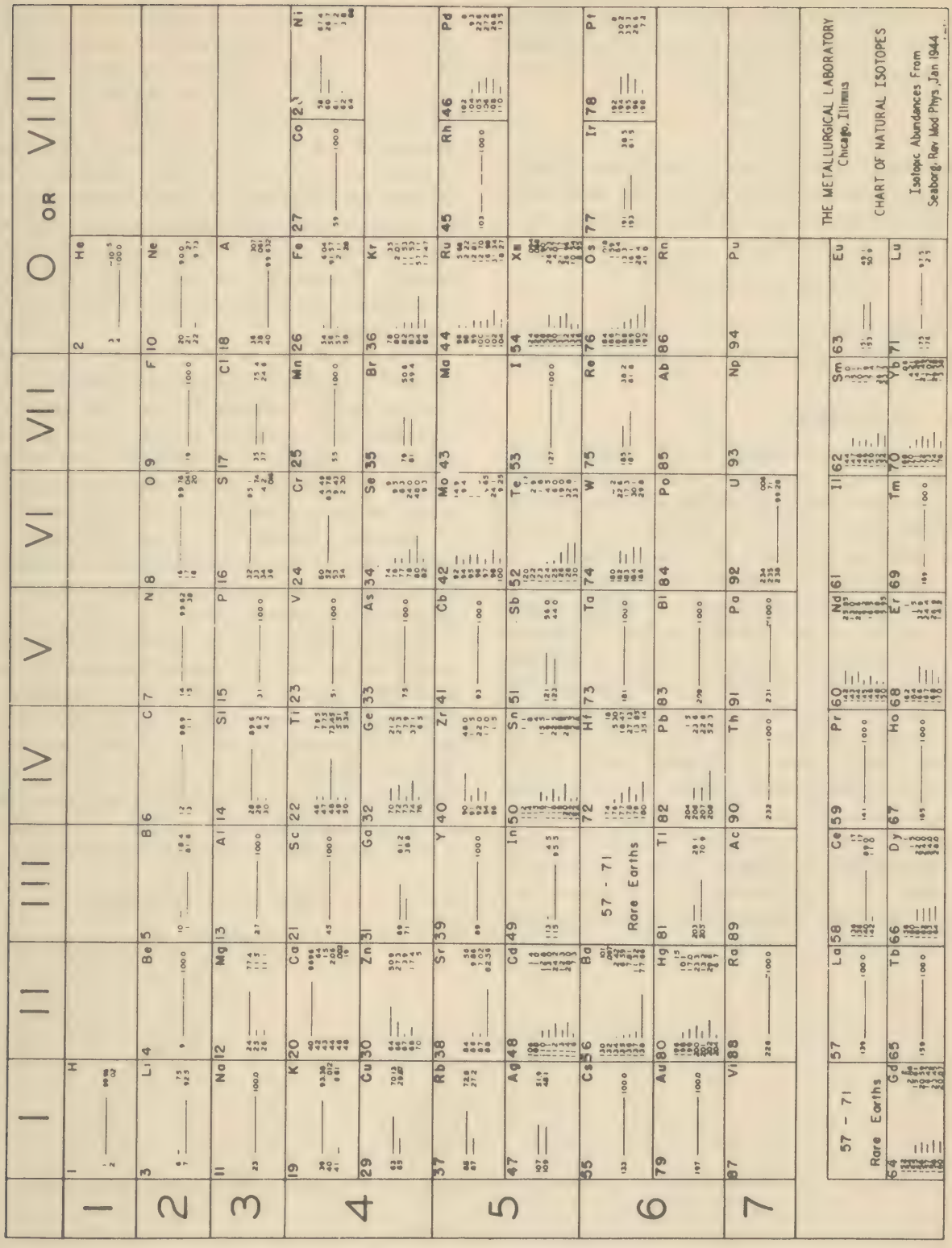


FIGURE 5–22.—Periodic table of the elements showing isotope abundance.

Inspection of this table shows that all the masses of the isotopes are approximately whole numbers. The difference between the mass number M of any isotope and the nearest whole number is called the mass defect and is written as Δ.

$$\Delta = M - A \tag{23}$$

A term which is often found in the literature is the packing fraction and it is simply the mass defect per nuclear particle. It is thus the same as the mass defect divided by A:

$$\text{Packing fraction } f = \frac{M-A}{A} \tag{24}$$

In this text these terms will not be generally used; they are included here for the sake of completeness.

5.15 Stable Isotopes

The relative abundance of the isotopes of tin has been given in table III. It is remarkable that this same abundance is obtained for any sample of tin, no matter where it was mined. Furthermore, the isotope ratio does not change with time, and there is no reason to believe that it ever will undergo a natural change. For this reason, tin is said to consist of *stable isotopes*. There are only a relatively few naturally occurring elements which do not always exhibit the same isotope ratio regardless of their origin. One of these is lead. It is found that samples of lead taken from the Belgian Congo show a different isotope ratio than lead mined in some other parts of the world. There is no reason to believe, however, that any sample of lead, independent of its origin, changes its isotopic ratio with time. Thus lead is said to be made up of stable isotopes. The reason why different samples of lead show different isotopic abundances will be explained in Ch. 6, sec. 6.07.

The term stability as applied to an isotope is really a relative term. It implies that during any time interval of observation the isotope does not change its atomic number or mass. Thus an isotope may be said to be stable if it remains unchanged for a period of time which is long compared with whatever time period the observer is concerned. As will be seen in chapter 6, some isotopes are unstable, i. e., they change their mass or charge in extremely short time intervals while others change over a period of many years. This concept of stability and instability will become clearer after the phenomenon of radioactivity has been discussed.

Figure 5–23 is an N–P diagram for stable isotopes. It simply represents a graphical plot of the number of neutrons for any isotope and the corresponding number of protons in the nucleus of the same isotope. The smooth curve which is drawn through the points representing all the stable isotopes of the 92 elements is called the *line of stability*. Initially the slope of this curve is almost 45°. With increasing proton numbers, the slope becomes increasingly steeper; i. e., the N/P ratio becomes greater than 1.

In figure 5–23, it will be noted that there is often more than one isotope having the same value of N plus P but having a different proton number. In fact there are some cases where isotopes of three different elements have exactly the same isotopic weights. Such isotopes are known as *isobars*. No cases are known where there are more than 3 isobars for any value of N plus P. An example of a triple stable isobar shown in figure 5–23 is:

$$_{40}Zr^{96},\ _{42}Mo^{96}, \text{ and } _{44}Ru^{96}$$

where

$$N + P = 96$$

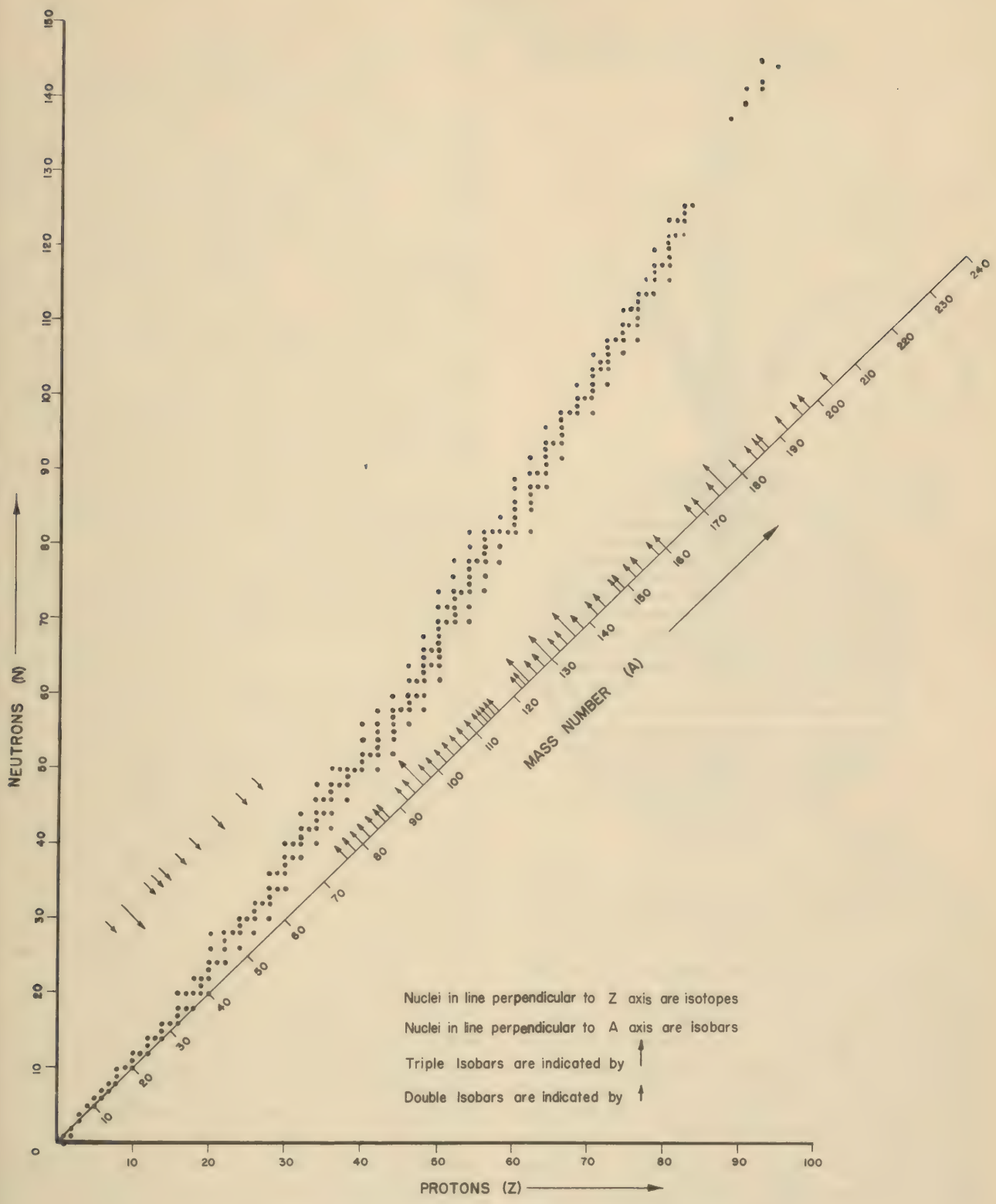


FIGURE 5–23.—Neutron-proton plot of stable isotopes.

Chapter 6

NATURAL RADIOACTIVITY AND NUCLEAR STRUCTURE

6.01 The Discovery of Natural Radioactivity

In the year 1896 a French physicist, Henri Becquerel, found that certain uranium salts emitted penetrating radiations similar to those which Roentgen had found only a year earlier. In finding that certain ores naturally give off rays similar to X-rays, Becquerel became the discoverer of the phenomenon of radioactivity. The tremendous importance of this discovery was not immediately apparent. However, a few years later, the Curies (Pierre and Marie) gave added stimulus to the investigation of the new field by announcing that they had succeeded in isolating from a uranium mineral (pitchblende) two substances which were many times more radioactive than uranium. These new substances were shown to be two new elements, polonium and radium. It is important to emphasize that these radioactive elements spontaneously emit radiation without the addition of energy. Later it will be shown that there is still another kind of radioactivity which is produced by adding energy to a nucleus in order to disrupt it. Such nuclei are said to be made artificially radioactive.

In addition to the radioactive elements which have been mentioned, the disintegration products from radium are also naturally radioactive. Investigation of the disintegration or decay products led to the identification of other radioelements ranging in atomic number from uranium (92) to bismuth (83). Such radioelements are now known to be intimately related to each other in what are called radioactive series. These series will be discussed in section 6.03.

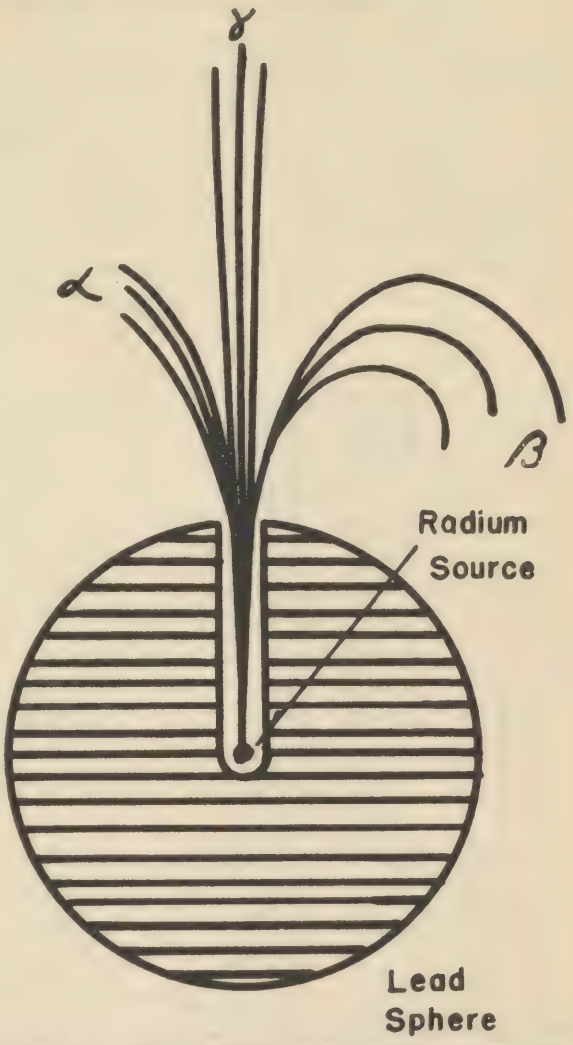


FIGURE 6–1.—Rays emitted from a radium source placed in a magnetic field. The field is perpendicular to the plane of the paper and directed inward.

6.02 Rays Emitted by Radioactive Elements

The problem of identifying the rays which are emitted by the radioactive elements was not an easy one, and the world's most skillful physicists worked for a period of several years before they were able to identify the mysterious radiations. Rutherford showed that some of the rays could be deflected by a magnetic field and thus separated from one another. It was actually shown that these rays were of three distinctly different types. In figure 6–1 a radium source is shown inside of a lead sphere into which is bored a small diameter hole. Since the sphere is thick enough to absorb the penetrating rays, the only way in which they can emerge is through the opening. Thus a parallel beam of radium rays escapes from the sphere. If one were able to see the trajectories of these invisible rays in the presence of a magnetic field, they would look as sketched in figure 6–1. Those most easily deflected by the magnetic field are called β (*beta*) *particles*. Those deflected only slightly by the field are called

α (*alpha*) *particles*, while those which are unaffected in their trajectories are known as γ (*gamma*) *rays*.

From the fact that the α-particles are deflected to the left in a magnetic field directed perpendicularly into the plane of the paper, it is known that they must be positively charged particles. By similar reasoning, the β-particles must carry a negative charge, and the γ-rays must be uncharged or electrically neutral.

Having thus investigated in a preliminary way the electrical nature of the radiations, it is natural to determine the penetrating power of each of the three types. To illustrate this, imagine an experiment of the type shown in figure 6–2. Here an extended radium source emits α- and β-particles and γ-rays. In *A* an absorber, consisting of a few sheets of ordinary paper, is placed over the source. The α-particles are stopped by the paper, but the β-particles and γ-rays pass through it without being diminished appreciably in intensity. In *B* the effect of an absorber, consisting of a few millimeters of aluminum sheet, is shown. Here both α- and β-particles are filtered out or absorbed by the aluminum, but the γ-rays are only slightly reduced in intensity by the absorber. Finally *C* shows that an absorber of 5 centimeters of lead greatly reduces the γ-ray intensity but does not completely absorb all the γ-rays.

Later on in this chapter, the problem of the emission of α- and β-particles and γ-rays from nuclei as well as the mechanisms of their absorptions in matter will be treated in detail. For the present, having indicated something about the electrical nature and penetrating power of the rays, a summary of other properties of the radiations is given.

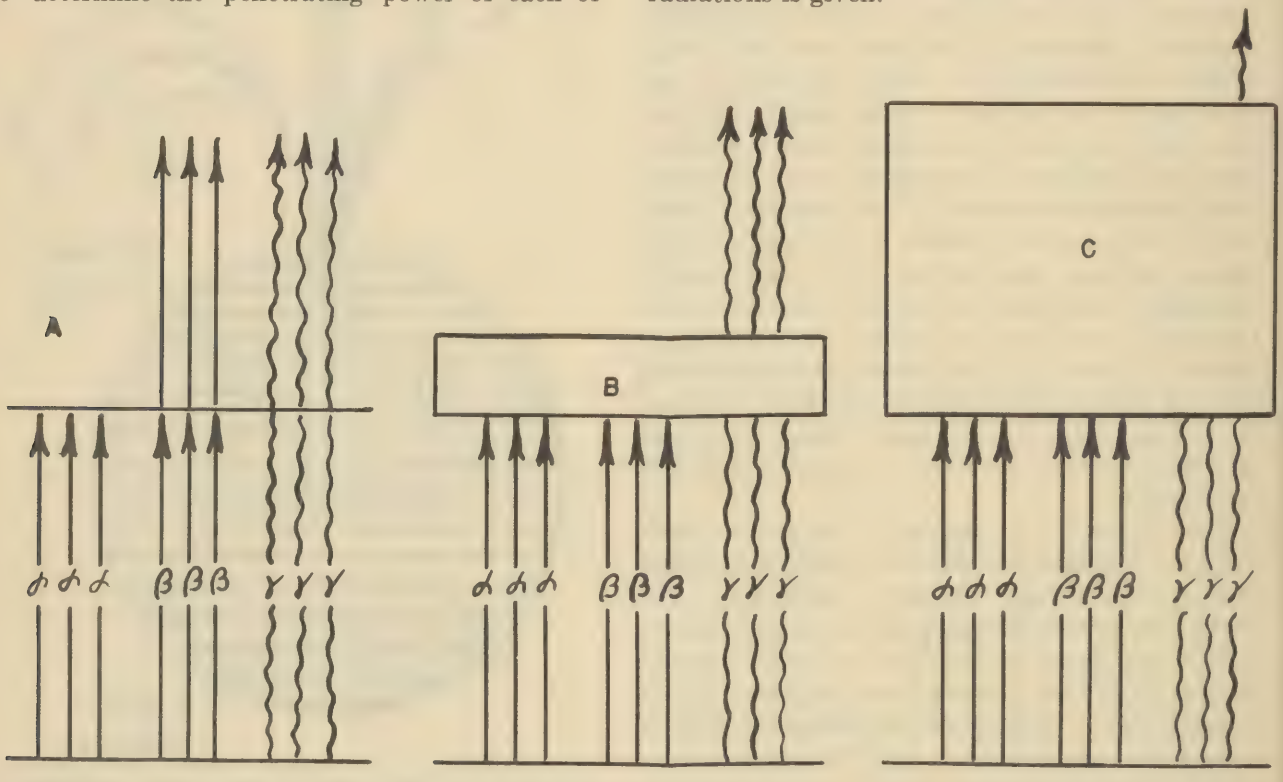


FIGURE 6–2.—Relative penetrating power of alpha, beta, and gamma radiation.

6.03 Alpha Particles

Experiments involving such instruments as the Wilson cloud chamber and magnetic spectrographs have shown that an α-particle carries a positive electric charge equal to exactly twice the electron charge. Furthermore, it has a mass the same as that of a helium nucleus and has, in fact, been shown to be exactly that. Thus α-particles are simply helium atoms, which carry a double positive charge and which are ejected from nuclei of radioactive isotopes with very high

velocity. The velocity with which these particles leave the nuceleus determines the distance which they will travel in any substance—this distance is called the *range* R of the α-particle. R is usually given in terms of the number of centimeters of air under standard conditions which the α-particle will traverse before being stopped. Range is related to the initial velocity v_0 of the α-particle by the simple relation:

$$v_0^3 = aR \qquad (1)$$

where a is a constant. As an example, an α-particle from RaC′ (a radioelement to be discussed later) has an initial velocity of 1.9×10^9 cm/sec., or less than $\frac{1}{10}$th the velocity of light, and has a range of almost 7 centimeters in air. Upon being stopped an α-particle picks up two electrons and becomes a normal helium atom. As evidence that the latter reaction occurs, it can be demonstrated that a strong α-emitter sealed in a glass capsule eventually produces enough helium gas to be identified by its characteristic atomic spectrum.

Simple absorption experiments show that for any given radioisotope which is an α-emitter there may be a series of ranges for the α-particles. These ranges can be classified in groups and yield valuable information about nuclear structure, in much the same way that optical spectra revealed the existence of atomic energy levels.

6.04 Beta Particles

A magnetic spectrographic analysis shows that β-particles have a single negative electrical charge equal to that of an electron, and that they also have a mass equal to that of an electron. Thus β-particles are simply high speed electrons which result from a nuclear disintegration. One should not jump to the conclusion that there are electrons as such within the nucleus, for such is not the case.

Beta particles emitted from nuclei may travel with velocities only slightly less than the velocity of light, i. e., about 0.95 c, where c is the velocity of light. In contrast with α-particles, which are found to have very definite ranges and, therefore, discrete energies, β-particles in general exhibit a continuous distribution of velocities. Thus, to these β-particles, only mean or average velocities can be assigned, and such β-particles are known as *primary* β-particles.

Another class of β-particles are emitted from certain atoms. These have discrete energies, analogous to α-particles, and are known as *secondary* β-particles. Unlike primary β-particles, these secondary rays do not originate in the nucleus, but are produced in the electronic outer shells of atoms by a photoelectric process discussed in the section 6.05.

Among the fastest or hardest β-particles which are known among the natural radioisotopes are primaries emitted by RaC (radium C, a decay product of radium). These particles have an upper energy limit of about 3.1 Mev, and travel with velocities only 1 percent less than that of light. In this connection, it can be observed experimentally in a strong electric and magnetic field that β-particles of this velocity have a mass greater than that which they have when traveling at low velocities. This startling fact, namely that the electron increases in mass with increasing velocity, is readily explained by Einstein's theory of relativity. A consequence of this theory is that the mass m of any body moving with velocity v is related to the rest mass m_0 of that body, i. e., $v=0$, by the relation

$$m = \frac{m_0}{\sqrt{1-\left(\frac{v^2}{c^2}\right)}} \qquad (2)$$

where c is the velocity of light (see sec. 2.04). If this equation is applied to an electron of rest mass m_0 moving with velocity $v=0.9c$, then its mass at that velocity is $m=2.3\ m_0$.

6.05 Gamma Rays

Gamma rays are photons similar in character to X-rays, but differing in that they are of shorter wave length. Radioactive nuclei emit γ-rays of discrete energies, and hence γ-ray spectra consist of a series of sharply defined wave lengths. However, in emerging from the nucleus, some of the γ-rays do not escape through the electronic cloud around the nucleus; instead they may transfer to one of the electrons sufficient energy to eject it from the atom. Photons thus absorbed within the electronic shells are said to be internally converted while the electrons ejected by the process are called *internal conversion* or secondary electrons. The process of internal conversion usually takes place in the K-shell, and in some atoms almost

all of the γ-rays emitted by the nucleus are internally converted. Since the nuclear γ-rays and the K electrons have discrete energies, the internal conversion electrons will be ejected with discrete energies. This process thus accounts for the line spectra of β-particles that is superimposed upon the continuous β-particle spectra of some radioisotopes.

Since γ-rays are of exactly the same physical nature as X-rays, they are also absorbed by the same processes, namely:

a—Photoelectric effect
b—Compton effect
c—Pair production

Wave lengths of γ-rays are often given in X-units, where 1 X-unit $=10^{-11}$ cms. The natural radioisotopes emit γ-rays of wave lengths ranging from 2 to 300 X. U. (X-units).

6.06 Statistics of the Decay Process

Very early in the history of radioactivity, it was discovered that the activity of the elements decreased with time. For a given quantity of a radioelement, the activity might decrease very rapidly in a matter of seconds, or it might change more slowly over a period of years. The rate of change of activity was found to be characteristic of the specific radioisotope under study. Figure 6–3 represents a graphical plot of a radioisotope which decreases in activity by a factor of 50 percent every four hours. If there is, say, 100 percent activity initially, after 4 hours there will be 50 percent left. After another 4 hours there will be 50 percent of this remaining activity, or only 25 percent of the initial amount. The time T which is required for a radioisotope to lose 50 percent of its activity is called its *half-life*. Two abscissa units are indicated in figure 6–3: one in hours, the other in multiples of the half-life, T. Figure 6–3, when plotted in terms of the half-life, is a universal curve which applies equally as well to the decay of an isotope with half-life $T=10^{-6}$ seconds as to one with $T=10^{7}$ years.

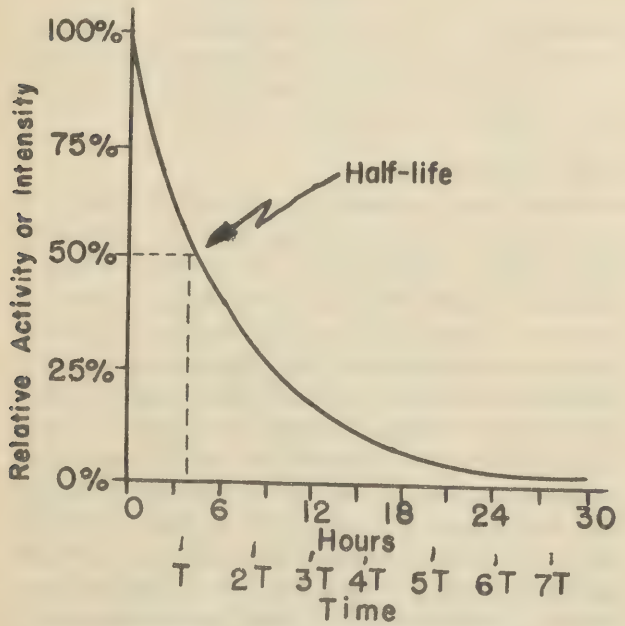


FIGURE 6–3.—Radioactive decay curve.

The form of the curve in figure 6–3 suggests that the decay is a logarithmic process. That is, if the activity is plotted on a logarithmic scale against the time on a linear scale, the resulting curve should be a straight line. Figure 6–4 illustrates that this is the case when a semi-logarithmic plot is made of relative activity versus time.

From an analytical viewpoint, the problem can be approached in the following manner: we know experimentally that radioactive decay takes place in such a way that the number of decays occurring per unit time is proportional to the total number of radioactive atoms present. Analytically, the number (ΔN) of atoms disintegrating in a given time interval (ΔT) is proportional to the number (N) of the radioactive atoms present.

$$\Delta N = -\lambda N \Delta t \qquad (3)$$

where λ is the constant of proportionality and is called the *decay constant*. The negative sign in the equation is introduced because the process leads to a decrease in the number of atoms with time. By means of calculus, this equation is integrated and yields:

$$N = N_0 e^{-\lambda t} \qquad (4)$$

where N_0 is the total number of atoms present at $t=0$. This equation expresses the number of particles N existing at time t when N_0 radioactive atoms were present initially. The range of validity of this equation is truly enormous, since it applies to processes which decay extremely rapidly ($T=10^{-6}$ seconds) as well as for those which decay slowly ($T=10^{11}$ yrs.).

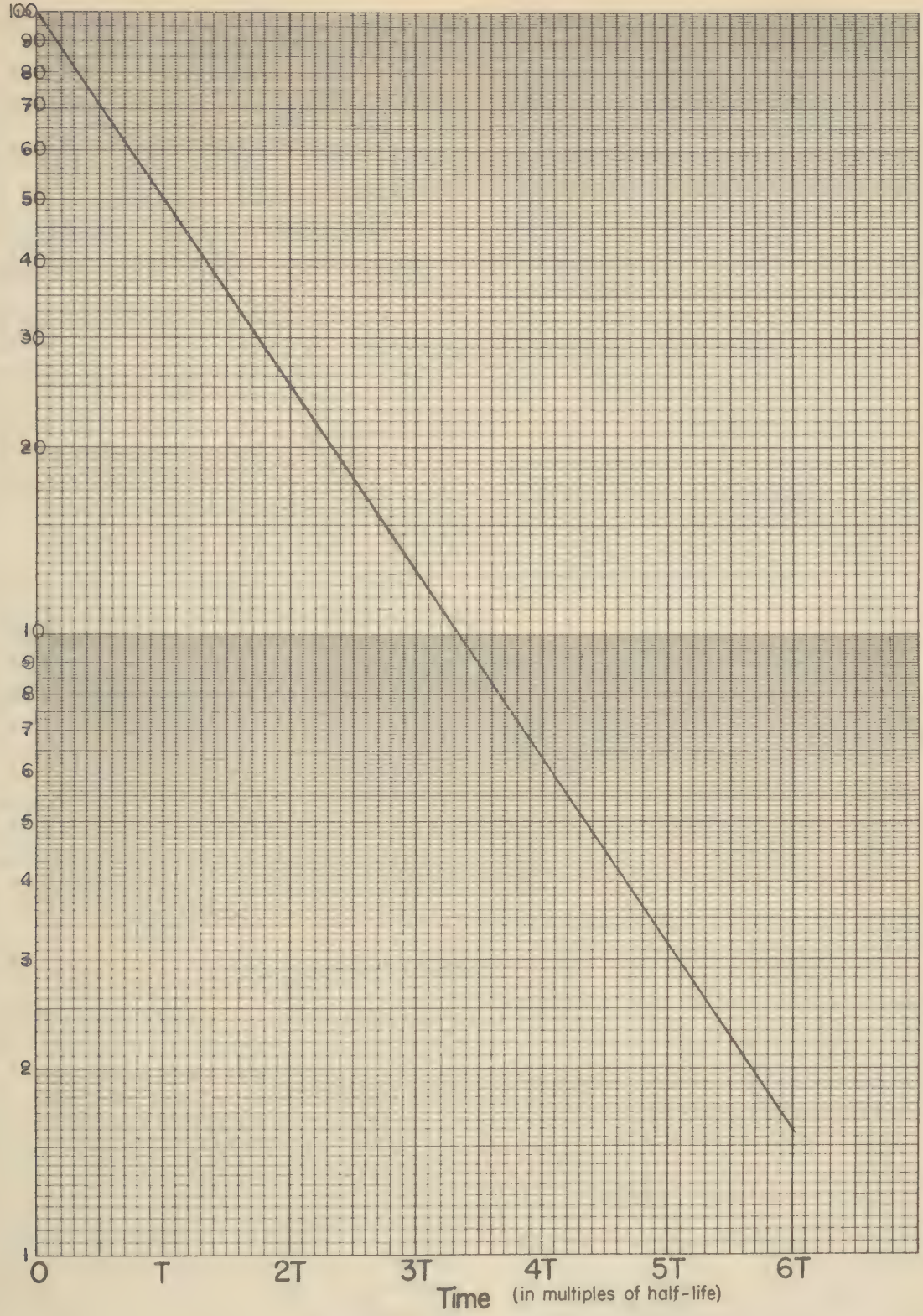


FIGURE 6–4.—Radioactive decay curve on a logarithmic plot.

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There is one condition that must be fulfilled in order for this equation to be rigorously applicable. That is, the total number of radioactive processes being considered must be sufficiently large so that statistical methods are valid. For example, in the case of a single isolated atom of half-life equal to 1 hour, there is only a probability that the atom will decay in any reasonable number of minutes either side of the 1 hour period. In fact, the atom might decay in the first second after $t=0$ (when observations are started) or it might decay 1 day after $t=0$. The process of decay is a statistical one which when applied to large numbers of atoms, as is usually the case, allows accurate calculations of the number of disintegrations which will occur in a given time interval.

It must be obvious that the disintegration constant λ and the half-life T are related to each other. Since the half-life was defined earlier as the time required for a substance to decay to one half of its initial activity, we can solve equation (4) for T in terms of λ by substituting $N=N_0/2$ at time $t=T$. Thus:

$$\frac{N_0}{2}=N_0e^{-\lambda T} \tag{5}$$

On converting to logarithmic form, it follows that since:

$$\ln 2=0.69$$

then:

$$T=\frac{0.69}{\lambda} \tag{6}$$

Any single radioisotope is characterized by a certain definite half-life which is constant and may often be used to identify it.

As an example of a simple numerical calculation involving the half-life and the disintegration constant, consider the emission of α-particles from radium. Experimentally, the half-life of radium is known to be 1590 years. By Eq. (6) the disintegration constant λ is equal to $\frac{0.69}{1.59\times10^3 \text{ yrs.}}$ or $5\times\frac{0.69}{10^{10} \text{ seconds}}$ or 13.8×10^{-12} sec^{-1}. Since the atomic weight of Ra is 226, and since there are 6.0×10^{23} atoms in one gram atom of Ra (by Avogadro's law), it follows that 1 gram of radium contains 2.6×10^{21} atoms. From Eq. (3) the expression $\frac{\Delta N}{\Delta t}$ is the rate at which an element decays, and for radium this rate for 1 gram is:

$$\frac{\Delta N}{\Delta t}=\lambda N=(13.8\times10^{-12})\ (2.6\times10^{21})$$
$$=3.7\times10^{10} \text{ disintegrations/second.}$$

This numerical quantity of 3.7×10^{10} disintegrations/second is known as the *curie* and is the standard unit used in measuring the activity of a radioactive substance. Often smaller units called the millicurie, *mc*, (1/1000 curie), and microcurie, μc, (1/1,000,000 curie) is used, since the curie is such a large unit. Recently a new unit, the rutherford, has been introduced. This is defined as that activity which is equivalent to 10^6 disintegrations per second.

Substances which have extremely long half-lives obviously have a low specific activity. The specific activity of a substance is the number of disintegrations occurring per second per gram. For example, the heavy isotope of uranium, U^{238}, has a half-life of 4.5×10^9 years, and 1 gram of it emits only about 12,000 α-particles per second and this is its specific activity.

It should be pointed out that the definition of the curie, which is based on the number of disintegrations and not on the number of radiations emitted, holds equally well for emission of α-particles, β-particles, and γ-rays.

6.07 Radioactive Series

Earlier it was mentioned that the radioactive element ${}_{88}Ra^{226}$ decayed by α-emission with a half-life of 1590 years to form radon or as it is sometimes known, radium emanation. This element (${}_{86}Rn^{222}$) is thus a decay product of radium. This reaction is shown schematically in figure 6–5. Emission of an α-particle from the nucleus of ${}_{88}Ra^{226}$ reduces the atomic number of the original atom by 2 charges, and the mass by 4 mass units. Analagous to the manner in which chemical reactions are represented by a reaction equation, the decay process can also be described by a nuclear reaction equation:

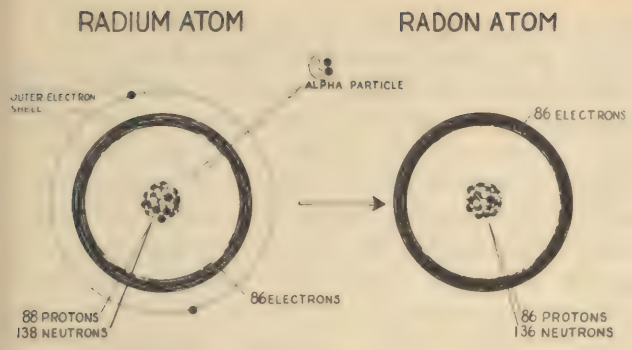

FIGURE 6–5.—Decay of radium to radon.

$$_{88}Ra^{226} \longrightarrow {}_{86}Rn^{222} + {}_{2}He^{4} + Q \qquad (7)$$

Just as in chemical equations, there has to be some type of a balance made on both sides of the equation. It will be noted that the superscripts representing the atomic masses add up to the same total on each side of the equation, as do the subscripts which represent the atomic numbers of the isotopes. In fact the equation for natural α-emission can be written in a more general form which applies to any element of atomic number Z and atomic mass A.

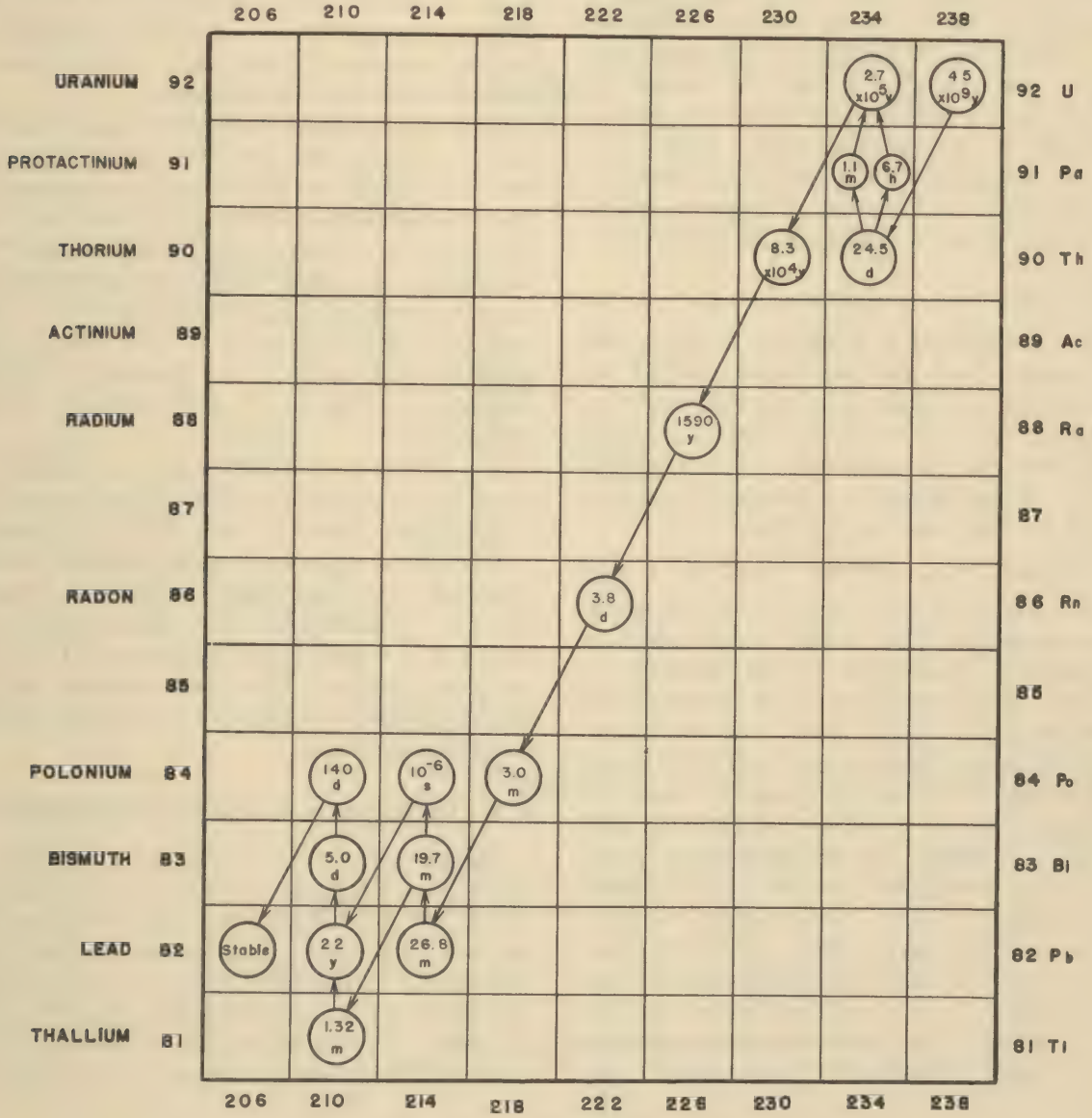

FIGURE 6–6.—The uranium series.

$$_{Z}\text{element}^{A} \rightarrow {}_{Z-2}\text{element}^{A-4} + {}_{2}He^{4} + Q \quad (8)$$

The quantity Q in each equation represents the energy which is released. Such energy manifests itself in the kinetic energy carried away by the high speed α-particle as well as by the recoil of the more massive radon atom.

Now if the radon atom were stable and thus did not decay into any other element, all the radium atoms would soon (speaking in terms of geological time) be converted into stable radon. Experiments have shown, however, that radon also undergoes disintegration by emitting an α-particle to form the decay product polonium, $_{84}Po^{218}$. Radon has a half-life of 3.8 days, and polonium, which is also radioactive, decays by α-emission with a half-life of 3 months to form a radioisotope of lead, namely $_{82}Pb^{214}$. Radio lead decays by β-emission with a half-life of about 27 months to form a radioisotope of bismuth, $_{83}Bi^{214}$. This latter process is described by the nuclear equation:

$$_{82}Pb^{214} \longrightarrow {}_{83}Bi^{214} + {}_{-1}e^{0} + Q \quad (9)$$

Thus the emission of a β-particle increases the atomic number by 1 unit but does not affect the atomic weight. In such equations the weight of the emitted electron is taken equal to zero to simplify balancing the equation. More generally the decay of any element by β-emission may be described by the following equation:

$$_{Z}\text{element}^{A} \rightarrow {}_{(Z+1)}\text{element}^{A} + {}_{-1}e^{0} + Q \quad (10)$$

Radium, radon, polonium, and the other radioelements mentioned thus form a series, which is diagramatically illustrated in its entirety in figure 6–6. This figure shows that radium is not the starting point of the series, nor would one expect it to be, for it has a relatively short (on a geological time scale) half-life; thus, if it were the start of the series, it would have long since vanished from the earth. At the head of the series is the heavy isotope of uranium, $_{92}U^{238}$, whose half-life, 4.5×10^{9} years, is longer than the geological age of the earth, about 2.5×10^{9} years. The end point of the series is the stable lead isotope, $_{82}Pb^{206}$. So far as the diagram of the series is concerned, an α-emission corresponds to a jump of 1 place (actually 4 mass units) to the left in the column of the diagram and also a descent of 1 place in the row of elements.

For certain purposes, figure 6–7 provides a more lucid presentation of the uranium series than does figure 6–6. In figure 6–7, the neutron number is plotted against the proton number for part of the uranium series. Beta reactions are clearly illustrated in this figure by an arrow slanting to the right. RaC can decay either by emitting an α-particle to form RaC″, or by β-decay to form RaC′. Such a phenomenon is known as *branching*. Table I lists all the isotopes in the uranium series and gives both the modern symbols, e.g. $_{82}Pb^{206}$, as well as the original terms, for the member of the series. Both types of terminology are in current usage.

Two other natural radioactive series similar to the one already described are known. One is the actinium series, and the other the thorium series. The former begins with $_{92}U^{235}$ and ends with $_{82}Pb^{207}$, while the latter originates from $_{90}Th^{232}$ and terminates at $_{82}Pb^{208}$. Thus each of the three series terminates with a different stable isotope of lead. In different parts of the world, where uranium and thorium are present in different amounts, lead is found with different isotopic composition.

In addition to the three radioactive series, there are also a few long-lived light elements which are radioactive. Table II lists these radioisotopes.

These light isotopes must be regarded as singly occurring and non-related radioactive elements, for there is no evidence to indicate that they are members of a transformation series. All the four radioisotopes have very weak specific activities and are difficult to measure even with extremely sensitive equipment.

6.08 Equilibrium in Radioactive Transformations

The process by which an element decays has already been discussed, but nothing has been said about the manner in which the resulting decay product builds up. For example, radium decays with a half-life of 1,590 years into its immediate decay product, radon, which has a half-life of only 3.8 days. It is obvious that the rate at which radon will build up is a function not only of the

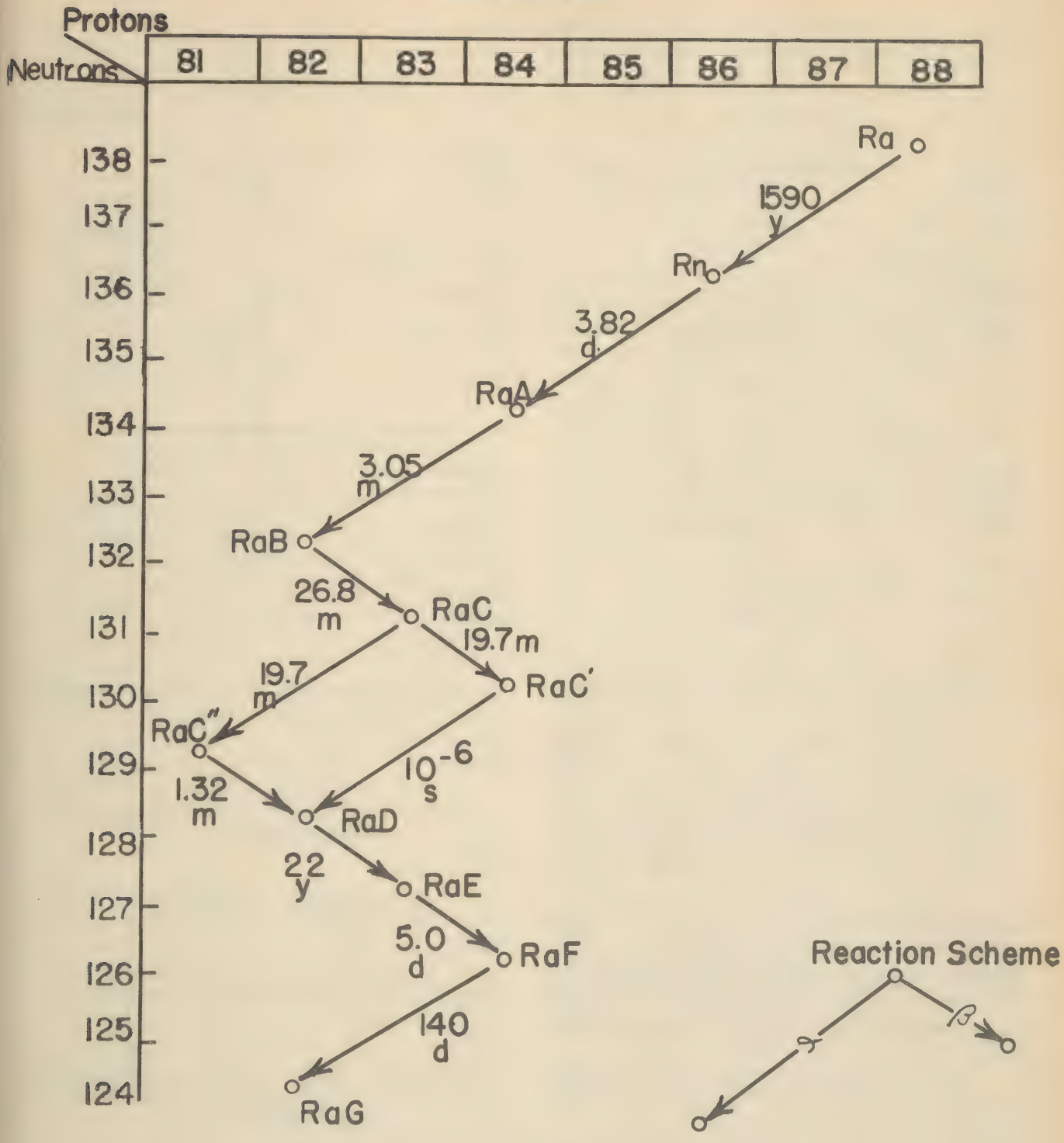

FIGURE 6–7.—A neutron-proton plot of the uranium series.

TABLE I.—*The Uranium Series*

Element	Symbols	Half-life	Particle emitted	
			Type	Range or energy
Uranium	$_{92}U^{238}$ (UI)	4.4×10^{9} years	α	2.67 cm.
Thorium	$_{90}Th^{234}$ (UX_1)	24.5 days	β^-	0.13 Mev.
Protactinium	$_{91}Pa^{234}$ (UX_2)	1.14 minutes	β^-	2.32 Mev.
			γ	0.80 Mev.
Uranium	$_{92}U^{234}$ (UII)	3.4×10^{5} years	α	3.23 cm.
Thorium (Ionium)	$_{90}Th^{230}$ (Io)	8.3×10^{4} years	α	3.2 cm.
Radium	$_{88}Ra^{226}$	1,590 years	α	3.39 cm.
			γ	0.19 Mev.
Radon	$_{86}Rn^{222}$	3.825 days	α	4.08 cm.
Polonium	$_{84}Po^{218}$ (RaA)	3.05 minutes	α	4.69 cm.
Lead	$_{82}Pb^{214}$ (RaB)	26.8 minutes	β^-	0.65 Mev.
			γ	
Bismuth	$_{83}Bi^{214}$ (RaC)	19.7 minutes	α	4.1 cm.
			β^-	3.15 Mev.
			γ	1.8 Mev.
Polonium	$_{84}Po^{214}$ (RaC′)	10^{-6} seconds	α	6.95 cm.
Thallium	$_{81}T1^{210}$ (RaC″)	1.32 minutes	β^-	1.80 Mev.
Lead	$_{82}Pb^{210}$ (RaD)	22 years	β^-	0.0255 Mev.
			γ	0.047 Mev.
Bismuth	$_{83}Bi^{210}$ (RaE)	5.0 days	β^-	1.17 Mev.
			γ	
Polonium	$_{84}Po^{210}$ (RaF)	140 days	α	3.87 cm.
Lead	$_{82}Pb^{206}$ (RaG)	Stable		

TABLE II.—*Naturally radioactive light elements*

Element	Isotope	Half-life	Type of emitter
Potassium	$_{19}K^{40}$	1.42×10^{9} years	β, γ
Rubidium	$_{37}Rb^{87}$	6.3×10^{10} years	β
Samarium	$_{62}Sm^{148}$	1.4×10^{10} years	α
Lutecium	$_{71}Lu^{176}$	7.3×10^{10} years	β

rate at which it is produced but also of the rate at which it decays. In considering this case, the problem is relatively simple, since the decay rate of radium is so slow that the number of radium atoms present at any time can be considered constant. Let

N_1=the number of radium atoms at any time t.

N_2=the number of radon atoms present at time t.

Then

$\lambda_1 N_1$=the number of radon atoms formed per second by decay,

where

λ_1=decay constant of radium.

Then

$\lambda_2 N_2$=the number of radon atoms decaying per second.

Let

ΔN_2=the increase of radon atoms that occurs in time interval Δt.

Then

$$\Delta N_2 = (N_1\lambda_1 - N_2\lambda_2)\Delta t$$

Upon integrating, and setting $N_2=0$ when $t=0$, it follows that:

$$N_2 = N_1 \frac{\lambda_1}{\lambda_2}(1-e^{-\lambda_2 t}) \qquad (11)$$

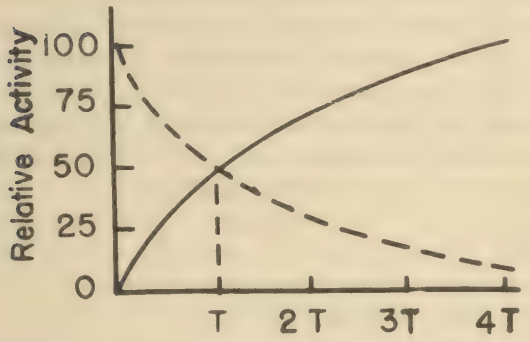

FIGURE 6–8.—Growth curve for a radioisotope.

This equation is plotted in Figure 6—8 to illustrate the way in which the new atoms of radon build up to an equilibrium value. This simply means that the radon is disintegrating at the same rate that it is being formed. Radon, which in a more general terminology would be called the *daughter*, is present in a constant ratio to the amount of the *parent* radium present. Equilibrium will be reached for a theoretical value of t equal to infinity. This causes the exponential term in Eq. (11) to drop out, leaving

$$N_2 = N_1\left(\frac{\lambda_1}{\lambda_2}\right) \qquad (12)$$

Radium is usually used in the form of a salt, generally as the chloride or bromide. A radium salt, freshly recrystallized to remove its decay products, shows little activity, for in its pure initial state in which no radon is present it emits only α-particles with a half-life of 1,590 years. As illustrated earlier, this would mean that it would be emitting only 3.7×10^{10} α-particles per second. When radium is in equilibrium with its decay products, it emits four times as many α-particles, actually 14.8×10^{10} α-particles per second. The radon disintegrates to form a daughter isotope, RaA, and the whole series of transmutations follows. The relation between radon and RaA is similar to that between radium and radon, for the rate of decay of each *daughter* equals the rate of decay of the *parent*. Thus Eq. (12) can be written for the whole series

$$\lambda_1 N_1 = \lambda_2 N_2 = \lambda_3 N_3 = \lambda_4 N_4 \ . \ . \ . \qquad (13)$$

Thus Eq. (12) can also be written

$$\frac{N_2}{N_1} = \frac{T_2}{T_1} \qquad (14)$$

where T_2 and T_1 are respectively the half-lives of the daughter and parent element. From this relation, it is significant that if one knows the ratio of any two elements in a radioactive series, such as uranium and radium, and in addition if the half-life of one element is known, then the half-life of the other element can be calculated. For example, radium occurs in natural uranium ore in the proportion of 1 atom of radium to 2.86×10^6 atoms of uranium. Since radium has a half-life of 1,590 years, then uranium must have a half-life equal to:

$$T_U = 1590\times2.86\times10^6 \text{ years.}$$
$$= 4.5\times10^9 \text{ years}$$

This value is in good agreement with experimental determinations of the half-life made in other ways. In cases where the parent atom is short-lived compared with the decay rate of the daughter, the calculation is somewhat more complex. This case is treated in advanced texts (Rutherford, Chadwick, and Ellis—"Radiations from Radioactive Substances") to which the reader is referred.

Since the age of the earth is estimated to be about 2.5×10^9 years, all radioactive elements which occur in nature must have half-lives of the order of 10^8 years, or they must otherwise be decay products of parents having half-lives of 10^8 years. On this basis more than one-quarter of the U^{238}, with a half-life of 4.5×10^9 years, has disappeared since the earth was created.

The curie, the unit of intensity for measurement of radioactivity, has been defined as that activity due to 3.7×10^{10} disintegrations per second. It was originally defined as the activity of that amount of radon which was in equilibrium with 1 gram of radium. At equilibrium conditions, both radium and radon decay at the rate of

3.7×10^{10} disintegrations per second so that both definitions are equivalent.

In specifying the activity of any substance, it is customary to refer to the number of atoms of the substance disintegrating per second even though it may not be an α-emitter.

The roentgen has already been defined as the amount of radiation which produces 1 electrostatic unit of ions in 1 cubic centimeter of air under standard conditions of temperature and pressure. Thus the roentgen unit is a measure of the ionization produced by X- or γ-radiation in a given sample of air, while the curie is a measure of the rate of emission of radiation by a radioactive source.

The roentgen unit applies only to electromagnetic radiation, and the curie is only a measure of the number of emissions with no reference to the energy of the radiations. It is obviously desirable to have a unit which will express both the number and the energy of radiated particles or quanta.

It can be shown easily that the definition of the roentgen unit is equivalent to requiring that 1.6×10^{12} ion pairs be produced in one gram of air under standard conditions. A national extension of this definition is the *roentgen equivalent physical* (*rep*). One *rep* is that quantity of ionizing radiation which is capable of producing 1.6×10^{12} ion pairs per gram of air.

Some radiations have an effect on biological tissue out of proportion to the amount of ionization produced, and consequently another unit of biological effectiveness is introduced. The *roentgen equivalent man* (*rem*) is that quantity of radiation which when absorbed by man produces an effect equivalent to the absorption by man of one roentgen of X— or γ— radiation. For example if a given flux of neutrons resulted in the production of 1.6×10^{12} ion pairs per gram but produced a biological effect equal to 5 r of gamma rays, 1 *rep* (neutrons) would equal 5 *rem*.

6.09 Equivalence of Mass and Energy

In Section 6.07 several nuclear reaction equations were used to describe the emission of α-particles from nuclei. In each equation, a term Q was used to take care of the energy carried away by the high speed α-particles and the recoiling nucleus. In the case of an α-particle emitted by radium, the α-particle leaves the nucleus with 4.79 Mev of kinetic energy. What is the source of this exceedingly high energy? To answer this question and to prepare the ground for the next section on the theory of α-emission, this section is devoted to a brief discussion of the equivalence of mass and energy.

Early in this century, Einstein resolved certain difficulties which were inherent in classical theories of mechanics and electrodynamics by proposing a radically new approach to the problems. Einstein set forth in his now famous theory of special relativity that the mass and energy of any physical system are related by the equation:

$$E=mc^2 \tag{15}$$

where

E is the energy of the system

m is its inertial mass

and

c is the velocity of light.

This equation states that any body having an inertial mass m also has a total associated energy E given by the product of its mass multiplied by the square of the velocity of light. On the basis of this concept, a 1 gram mass of an element is equivalent to an energy of

$$E=1\ (3\times10^{10})^2=9\times10^{20}\ \text{ergs}$$

and since 1 erg $=2.78\times10^{-14}$ kilowatt hours

$$E=25{,}000{,}000\ \text{kilowatt hours.}$$

On the face of it, this seems absurd for 1 gram of an element to be equivalent to 25 million kw. hr., for this is truly an enormous amount of energy. In thermal units, it is equal to 85 billion b.t.u. or 21×10^{12} calories of heat energy.

A similar calculation applied to the energy content of a single hydrogen atom shows that it is equivalent to 931 Mev of energy. However, Eq. (15) does not state that the energy E is releasable; all that it states is that if all the mass (m) could be somehow converted into energy, then the quantity mc^2 of energy would be released. To appreciate the fact that an extremely small change in mass of a system produces a very large change in energy, consider first the combustion of coal. This chemical reaction is written simply as:

$$C+O_2 \longrightarrow CO_2+Q \tag{16}$$

where

Q=the thermal energy released.

If 1 pound of carbon burns completely to form the single end-product carbon dioxide, it is known that Q=about 4 kilowatt hours of energy (in the form of heat); 3.67 pounds of CO_2 result from the chemical reaction, and in comparison with this amount of material, the mass equivalent of 4 kw.-hr. of energy is exceedingly small, being only 3.7×10^{-10} pounds. Therefore, in order to detect the change in mass in this reaction, one would have to measure 3.7×10^{-10} lbs. in a 3.67-pound total sample. Weighing to an accuracy of 1 part in 10^{10} is beyond our present means of chemical analysis. In fact, the most sensitive micro-balance can measure about 1 part in 10^7, so that it is not possible to measure the mass difference between the elements on the left-hand side of Eq. (16) and that on the right. This statement is equally true for any purely chemical reaction, for the reaction which has been discussed is an extremely energetic chemical reaction. The mass change is so small as to be a thousand times too slight to detect with even the best micro-balances.

When nuclear reactions are considered, the situation is quite different. The energy released is many fold larger than that liberated in a chemical reaction. In the chemical burning of 1 atom of carbon, about 1 electron volt of energy is released, whereas in the emission of an α-particle from radium, 4.8 Mev are released. Thus, per atom of carbon, nearly 5 million times more energy and more mass are released. Now 4.8 Mev of energy is equivalent to a mass of 8.6×10^{-27} grams. A single radium atom weighs about 3.6×10^{-22} grams, so that it should be possible to measure the loss in mass that occurs in the reaction given by:

$$_{86}Ra^{226} \longrightarrow {}_{84}Rn^{222}+{}_{2}He^{4}+Q$$

The ratio of mass lost to original mass is 1 to 40,000. Through the use of mass spectrographs, mass differences as small as 1 part in 40,000 can be measured, and it found that the Einstein mass energy relation is verified.

6.10 Nuclear Binding Energy

The exact measurement of nuclear masses with mass spectrometric equipment makes it possible to calculate the energy with which nuclei are bound together. Consider any nucleus of mass M (accurately measured) which contains N neutrons and P protons. Both the mass of the neutron (m_n) and that of the proton (m_p) have been accurately measured and are known to be:

$$m_n = 1.00893 \text{ m.u. (atomic mass units)}$$
$$m_p = 1.00813 \text{ m.u}$$

But, by definition, the atomic mass unit is a mass equal to 1/16th of the mass of the $_8O^{16}$ isotope. 1 mass unit equals 1.67×10^{-24} g. Suppose that one calculates what the mass of this nucleus should be if it is simply the sum of the masses of the individual neutrons and protons inside the nucleus. Let this value to be calculated be W then

$$W=Nm_n+Pm_p \tag{17}$$

From the Einstein equation, it follows that the total energy associated with this mass is obtained by multiplying the right hand side of the equation by the factor c^2.

To illustrate the application of Eq. (17), let N=2 and P=2 so that the value calculated is W; i. e., the theoretical mass of the two neutrons and two protons which make up an α-particle.

$$W=2\ (1.00893)+2\ (1.00813)$$
$$=4.03412 \text{ mass units.}$$

The mass spectrographic value for the observed mass M of the helium nucleus is

$$M=4.00389 \text{ mass units}$$

The difference in mass (ΔM) between the observed and calculated value is

$$\Delta M = W - M = 0.03023 \text{ m.u.}$$

By previous definition, this quantity ΔM is called the mass defect. Since 1 mass unit is the equivalent of 931 Mev, the mass defect for a helium nucleus is $(0.03023)\times(931 \text{ Mev})=28.1$ Mev. In other words, if one were to synthesize a helium nucleus by some imaginary process using 2 neutrons and 2 protons, the resulting nucleus would be lighter than the total mass of the original particles by 0.03 mass units, which has disappeared to form 28 Mev. The mass which has been lost in the reaction when converted into energy units is called the binding energy of the nucleus. Table III lists the atomic masses which have been measured for some of the lighter elements. Other quantities listed are the mass defects, binding

energies, and binding energy per nuclear particle. A further discussion of the binding energy per nuclear particle is postponed to Chapters 7 and 8. The fact that 28 Mev of energy is liberated in the imaginary fusing together of 2 neutrons and 2 protons to form a stable helium nucleus implies that if this stable assembly of particles is to be smashed up into its separate components, then energy must be supplied to the nucleus from some outside source. The reason why energy must be added to a nucleus in order to disrupt it is that the neutrons and protons within the nucleus stick together, each nucleon being bound to the system by an energy which is about 8 Mev for most nuclei. What, then, is the physical nature of the nuclear forces which bind nucleons together?

TABLE III.—*Binding energies for light elements*

Stable atom	Atomic mass (in mass units)	Mass defect ΔM	Binding energy B_{Mev}	Binding energy per particle $BEPP_{Mev}$
$_0n^1$	1. 00893	------	-----	-----
$_1H^1$	1. 00813	------	-----	-----
$_1H^2$	2. 01473	0. 00233	2. 17	2. 17
$_2He^3$	3. 01698	. 00821	7. 72	2. 58
$_2He^4$	4. 00389	. 03022	28. 1	7. 03
$_3Li^6$	6. 01686	. 03432	32. 3	5. 40
$_3Li^7$	7. 01818	. 04191	39. 0	5. 57
$_4Be^9$	9. 01504	. 06213	58. 6	6. 51
$_5B^{10}$	10. 01631	. 06899	64. 8	6. 48
$_5B^{11}$	10. 01292	. 08131	71. 6	6. 50
$_6C^{12}$	12. 00398	. 09834	91. 6	7. 63
$_6C^{13}$	13. 00761	. 10368	96. 5	7. 42
$_8O^{16}$	16. 00000	. 13642	127. 0	7. 94
$_{10}Ne^{22}$	21. 99864	. 18975	176. 7	8. 03
$_{11}Na^{23}$	22. 99680	. 19971	185. 9	8. 08
$_{16}S^{33}$	32. 98260	. 29916	278. 5	8. 44
$_{17}Cl^{35}$	34. 98107	. 31776	295. 8	8. 45

6.11 Nuclear Forces

On the basis of the laws of physics which have been discussed up to now, one might attempt to explain nuclear forces in either of two ways. First, it might be assumed that the forces are coulomb or electric forces. However, such an assumption only illustrates that the nucleus should not be bound together at all, for the only charged particles in the nucleus are protons, and these being of like charge and close together would repel each other and constitute a disruptive force. Second, it might be assumed that the forces are gravitational. Now the gravitational force between two particles m_n and m_p (neutron and proton as in the deuterium nucleus) separated by a distance r is given by

$$F = G\frac{m_p m_n}{r^2} \tag{18}$$

where G is the gravitational constant and is $=6.66 \times 10^{-8}$ gram^{-1} cm^3 sec^{-2}. Here the force would be an attractive one, but for a value of $r = 10^{-13}$ cms., which is a typical separation for nucleons, the force between a neutron and proton is extremely small. Actually the force is about 10^{38} times less than that required to account for the observed binding energy of the deuteron.

Since neither of these assumptions lead to a solution of the problem, it is necessary to assume that nuclear forces are of a new type not previously found in physics. From experimental data certain characteristics of this new type of force are known. These are:

(*a*) The force is always attractive.

(*b*) It does not depend on the nature of the nucleon, i. e., whether it is a neutron or proton.

(*c*) Its range is very short, of the order of 10^{-13} cms.

(*d*) Nuclear forces show a saturation effect.

According to the second characteristic, the force which binds a neutron to a proton or a proton to another proton is about the same in magnitude. The force between a neutron and another neutron, called the neutron-neutron force, is also about the same as the neutron-proton force. The third characteristic is perhaps the most striking. Up to a distance of about 10^{-13} cms. the nuclear force has a constant value; beyond this critical distance, the force drops rapidly in value to zero. In this respect, the nuclear force differs from the coulomb force, which obeys an inverse square law and always has a non-zero value. The last characteristic of a nuclear force, namely, the saturation property, is very important. It can be explained in terms of a *pairing* of nucleons within the nucleus. That is, each tends to pair off with another nucleon, so that it effectively exerts a force only within a small group of nucleons. This surprising characteristic of a nuclear force accounts for the fact that no isotope of mass number 5 exists in nature. The four nucleons making

up a helium nucleus form a closed system in which each nucleon is fully saturated with respect to its interaction with the other three nucleons. As a result, these nucleons do not attract an additional neutron or proton to form an isotope of mass 5. Isotopes of mass 6 and higher exist because these nuclei do not contain a subnuclear system having the configuration of a helium nucleus. Thus, $_3Li^6$ is not a system composed of 1 α-particle, 1 neutron and 1 proton. It is, instead, a system of 3 neutrons and 3 protons, all of which interact and exhibit saturation.

If the nucleons did not exhibit saturation, the binding energy of a nucleus would be proportional to the square of the total number of nucleons within it. This is not the case for $_3Li^6$ nor for heavier isotopes. Another way of looking at the phenomenon is to point out that the additional neutron which one would like to add to the $_2He^4$ nucleus is forbidden from occupying the same virtual orbit within the nucleus as the other four nucleons because these orbits, analogous to electronic orbits, have a definite upper limit to the number of occupants they can tolerate. Consequently the additional nucleon must go into an orbit which is so far removed from the others that the short range nuclear force is not effective and the nucleon is not bound to the other four particles.

Just as Bohr developed the concept of atomic structure, he likewise advanced a model of nuclear structure. Basing his ideas on the characteristics of nuclear force as they are outlined above and upon the fact that only certain ratios of neutrons to protons are allowed for stable atoms, Bohr proposed that the nucleus could be thought of as a compact aggregation of nucleons, all in a constant state of motion and yet restricted to motion within the confines of a sphere of small radius. On this model, the nucleus corresponds to a small sphere of liquid, the constituents of which are nucleons which are fairly uniformly distributed throughout the sphere. For this reason, the Bohr model of the nucleus has been called the liquid drop model. Since the nucleons move with high speed within the nucleus and since this nucleus is extremely small in diameter, these particles make many collisions per second, and all tend to have the same average energy. It is therefore easy to see that the nucleus has a uniform density.

The short range nuclear forces which have been introduced into the discussion are known in quantum mechanics as resonance or exchange forces. These forces are not well understood, and much of the current research in physics is directed toward understanding the nature of the neutron-proton interaction.

It should be realized that the coulomb forces of the protons continue to act even though they are in the nucleus. One can picture the process as a superposition of the coulomb field on the nuclear force field. Thus the presence of a large number of protons in a nucleus, as in heavy nuclei, presents a repulsive force which tends to disrupt the entire nucleus. It is for this reason that the heavy stable isotopes have more neutrons than protons in their nuclei. The number of neutrons which can be added to nuclei is limited by an exclusion principle which requires that such additional particles go into higher nuclear orbits where the short-range force of nucleons is not effective. These two factors make the shape of the stability curve (shown in fig. 5–23) understandable.

6.12 Nuclear Potential Barriers

While the foregoing section has involved a discussion of nuclear forces, it would have been equally suitable to carry out the discussion using the concept of potential energy rather than force. The forces may be derived from the mutual potential energies of particles in a system. (See fig. 6–9.)

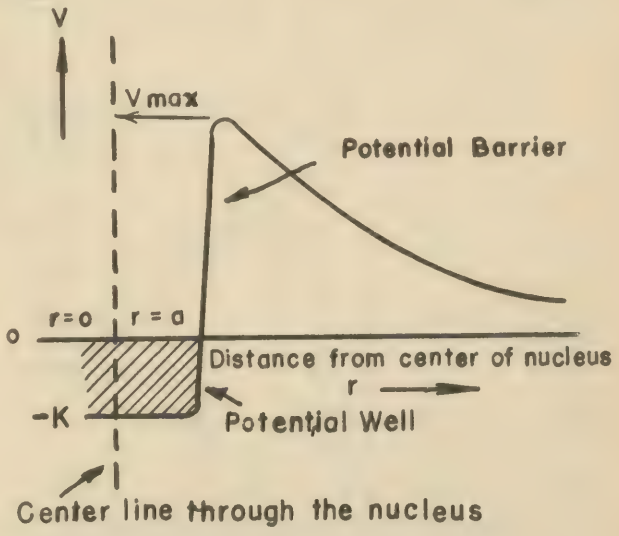

FIGURE 6–9.—Potential energy curve for a nucleus.

There is sketched a potential energy V curve for a nucleus as a function of the distance r from the center of the nucleus. At large distances, actually for any value of $r>a$, where a is the nuclear radius, the potential obeys the usual $1/r$ law. At a distance $r=a$ or for any value of $r<a$, nuclear forces are effective, and the potential energy drops to a constant value $= -K$ independent of the value of $r<a$. In the sketch this is shown as a *potential well*. For light nuclei, this potential well lies so low that it has a negative potential energy value. Let V_{max} be the potential corresponding to the height or maximum value of the *potential barrier*. For any two charged particles which form a system, the value of V_{max} depends on the nature of the two particles. For example, for two light particles, such as two deuterons, the barrier is only a few tenths Mev, whereas for heavier nuclei, V_{max} may be larger than several Mev. The concept of a potential barrier may be used in considering how two isolated particles will interact when brought close together; or it may be used in analyzing the resistance of a single system to disruption. In chapter 8, the former type of reaction will be discussed while the latter type of reaction will be described now.

6.13 The Theory of Alpha Emission

Figure 6–10 shows the potential energy distribution for a radium nucleus. Now consider the process by which an α-particle is ejected to form the daughter atom radon. If the α-particle were at a distance, say, $r=b$, away from the center of the nucleus, then it would be repelled. For r equal to the nuclear radius a and for smaller values of r, the α-particles will be held within the nucleus. Suppose that inside the nucleus, the α-particle has a potential energy $V=V_\alpha$ as indicated by the dashed horizontal line. It is obvious that while the α-particle is inside, it possesses a potential energy which is greater than that at any value of $r>$c. This statement is true for at any value of $r>c$, the α-particle is outside the nucleus and is experimentally observed to travel with considerable kinetic energy. This could only have been gained from the potential energy which the α-particle had in the nucleus. However, in order for the α-particle to escape, it must somehow or other get over the potential barrier.

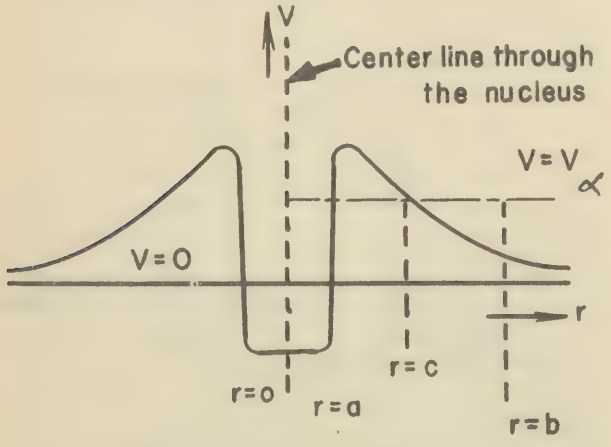

FIGURE 6–10.—Potential barrier for radium.

From the standpoint of classical physics, the α-particle is doomed to spend an eternity trapped within the potential barrier for there is no means by which it can spontaneously acquire enough energy to hurdle the potential barrier. Thus classical physics offers no explanation of spontaneous or natural emission of α-particles.

Modern physics, as exemplified by wave mechanics offers a solution to this impasse. It takes account of the wave nature of the α-particle and shows that there is a small but finite probability that the α-particle may leak through the potential barrier. The theory as developed independently by Gamow, and by Condon and Gurney, even calculates the average time required for the α-particle to penetrate a given potential barrier. These calculated times are in fair agreement with the observed half-lives of α-emitters. The theory further states that the time which the α-particle will take to leak out through a given barrier depends very critically upon the height (V_{max}) of the potential barrier. It is beyond the scope of this manual to present more detailed treatment of the theory of α-emission. Such a treatment may be found in Gamow's "Atomic Nuclei and Nuclear Transformations." One of the notable successes of the theory is that it accounts for the extreme range of half-lives which are found in nature and in fact shows that the disintegration constant of an α-emitter is simply related to the range or energy of the emitted particle. In 1911, two physicists, Geiger and Nuttall found that the

range R of an α-particle is related to its disintegration constant λ as follows:

$$\log R = A + B \log \lambda \qquad (19)$$

where A and B are constants.

According to this relation, α-emitters which have the longest half-lives emit α-particles of the shortest range. For example, an α-emitter which emits α-particles of 1 cm range has a half-life of about 2×10^{11} years. Such an element emits particles so infrequently it may almost be regarded as completely stable. On the other hand, α-emitters giving off particles of 6 cm range in air (about 7 Mev) have half-lives about 10^{-3} seconds. The Geiger-Nuttall relation is plotted in figure 6–11 where it is seen that members of each radioactive series fall on a straight line.

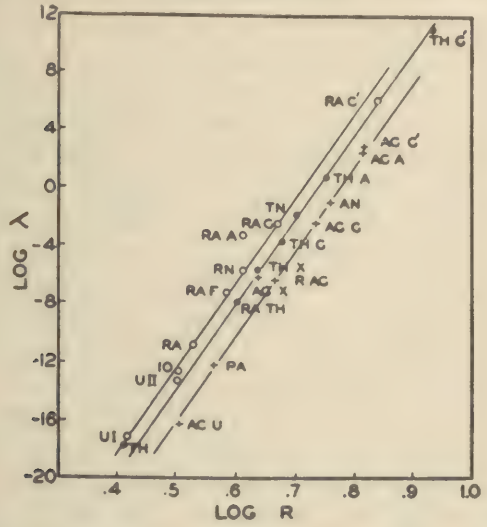

FIGURE 6–11.—Geiger-Nuttall relation for the three radioactive series.

6.14 Absorption of Alpha Particles

Certain rather general properties of α-particles have already been mentioned; it remains to develop a more detailed picture of the interaction of α-particles with matter, to discuss the mechanism by which α-particles lose energy, and to examine in detail some aspects of α-particle spectra.

(*a*) *Range in air and in tissue.*—Wilson cloud chamber photographs of α-particles (see fig. 6–12) show that for any given α-emitter, the alpha tracks observed are usually very straight, heavily ionized tracks characterized by a definite range. Tracks as seen in a cloud chamber correspond to the usual range of α-particles in centimeters of air, for in general these devices are operated with a gas not much different from air and at approximately atmospheric pressure. When ranges in air are given, it is understood to mean air under standard conditions (0° C. and 760 mm. pressure).

Figure 6–13 shows the experimentally obtained relation between the range of α-particles in air and the corresponding energy of the particles. For low energies, this curve corresponds to a

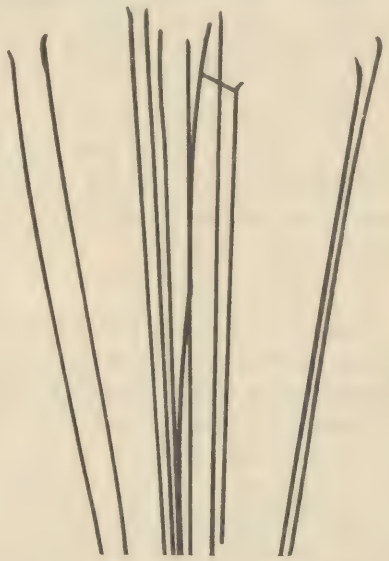

FIGURE 6–12.—Alpha particle tracks in a Wilson cloud chamber.

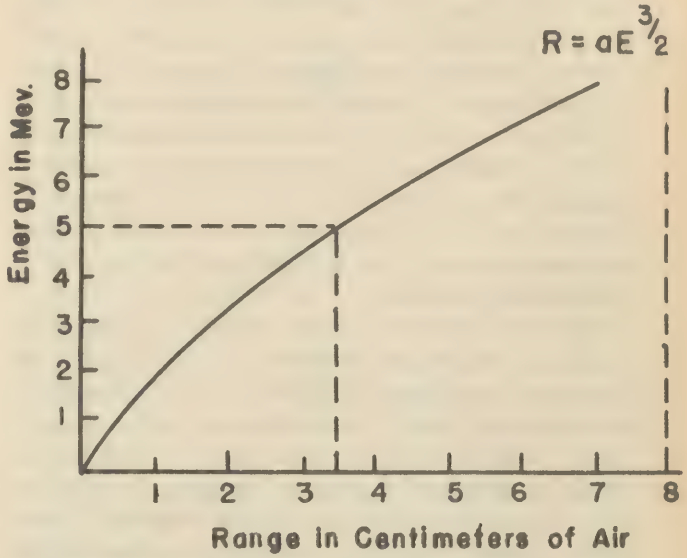

FIGURE 6–13.—Range vs. Energy curve for alpha particles in air.

plot of the function $R=aE^{3/2}$, where a is a constant and E is the energy of the α-particle. At high energies the range deviates from the 3/2 power law. From it, a 5 Mev α-particle is seen to have a range of 3.5 cms. of air. The range of α-particles when given in terms of centimeters of air is far greater than the distance these same particles would travel in human tissue. As an example, consider the range in tissue of a 5 Mev α-particle. Now since human tissue has a density of about 1, the range in it can be obtained by multiplying the range of the particle in air by the density of air. This follows from the relation

$$R_{\text{air}} \times \rho_{\text{air}} = R_{\text{tissue}} \times \rho_{\text{tissue}} \qquad (20)$$

where ρ refers to the density of the absorber.

Thus a simpler equation results by taking the approximate value of the density of tissue and substituting it in Eq. (20).

$$R_{\text{tissue}} = 0.00129\ R \qquad (21)$$

Here the symbol R has been substituted for R_{air} since the two are synonymous, and the density of air has been taken as 0.00129 gms/cc. Therefore a 5 Mev α-particle has a range in tissue of (0.00129) (3.5)=0.0045 cms. It is customary to express this range, since it is so small, in other units of length, namely, in microns. A micron (μ) equals 0.0001 cms (10^{-4} cms), and thus a 5 Mev α-particle has a range of 45μ in human tissue. Even the most energetic alphas cannot penetrate more than 70μ into tissue. This should not be interpreted as meaning that α-particles are ineffective in producing biological changes in tissue. On the contrary, since these particles expend all of their enormous energy in such a localized section of tissue, they may produce very significant biological effects. As will be shown in chapter 13, the danger from α-particles is acute when α-emitters are taken into the human body (by ingestion, inhalation, or incision).

(*b*) *Alpha particle spectra.*—Just as a mass spectrograph may be used to sort out and identify the isotopes of an element, likewise a spectrograph of similar design may be used to sort out the α-particles emitted from any isotope. When this is done, it is found that some α-emitters may give off groups of α-particles, each of which has a discrete range (energy). In general, an α-emitter gives off one group of α-particles with greatest intensity and emits a low intensity of other groups of different energy. ThC″, for example, emits seven α-particle lines or groups. For a long time, polonium was thought to emit monoenergetic alphas of 5.3 Mev, but careful investigation has shown that it probably emits at least 12 lines or discrete groups. These have, however, very weak intensities compared with the principal group, which has 5.30 Mev energy, and is emitted with intensity about 5,000 times larger than that of any other polonium group. The α-particle spectra are important in that they reveal the existence of discrete energy states or levels within the nucleus. This point will be amplified in discussing the origin of nuclear γ-rays (sec. 6.17).

(*c*) *The interaction of alpha particles with matter.*—Cloud chamber photographs show that α-particles produce dense ionization along their tracks. As the relatively massive, doubly-charged α-particle passes through the atoms of a gas, it makes frequent collisions with the outer, loosely bound electrons of the gas atoms. The electric field of the α-particles sweeps across the outer electrons, accelerates them, and pulls many of them from their shells. Thus many gas atoms are ionized. This process of ionization results in a detached electron and an ionized gas atom (an *ion-pair*). In the process of ionization, the α-particle has to supply energy to the gas atoms to cause an ion pair to be formed. On an average, this process requires about 33 electron volts per ion pair formed. In addition to energy lost by ionization, the α-particle also yields energy to neutral gas atoms by excitation. That is, it causes electronic transitions which are not sufficient to allow the electron to escape from its atom. By these processes, the α-particle continues to lose energy, and thus it is slowed down. As it slows down, the α-particle spends more time in the vicinity of any gas atom and consequently it has a higher probability of ionizing more and more atoms. If one defines the number of ion pairs formed per centimeter of air as the *specific ionization*, it follows that this quantity should be fairly constant when the α-particle is moving with high energy, but it should increase as the α-particle slows down to low energies.

By merely counting the separate droplets along the track of an α-particle in a cloud chamber picture, one may determine the specific ionization of the particle. In figure 6–14, there is

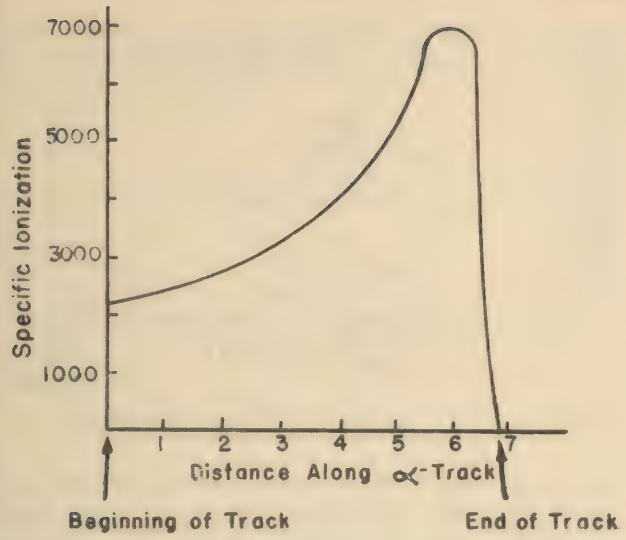

FIGURE 6–14.—Specific ionization vs. distance for alpha particles from radium C.

shown a curve obtained for the specific ionization of α particles from RaC as a function of the distance along the track of the particle. Within a few mms. of the end of its range the specific ionization drops very rapidly to zero.

If a monoenergetic group of α-particles is carefully studied, it will be noticed that while the group has a fairly definite range, there will be some alphas which have a shorter and others longer range than the average range for the group. This phenomenon is illustrated in figure 6–15. Here, it is seen that if all the alpha particles had the same range R, the number of alphas as a function of range would be constant and then break sharply at a value of the range $=R$; in other words it would follow the dotted curve at A. Actually the curve breaks before the point R, bending gradually at B and extending past R to

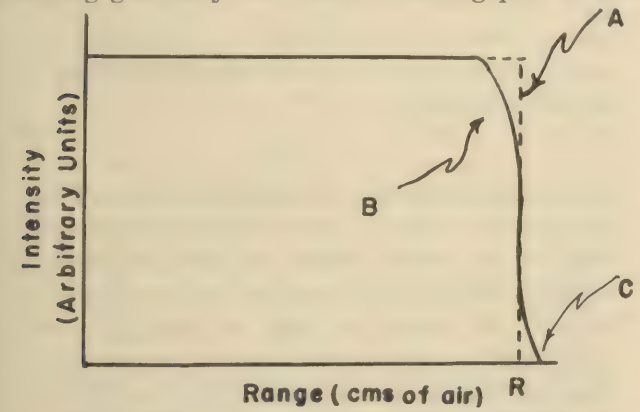

FIGURE 6–15.—Straggling of alpha particles.

point C. Accordingly, it becomes a question as to what one should accept as the true range for α-particles. This is a question of more concern to physicists than it is for practical considerations, and the reader is referred to any advanced text for a discussion of the problem.

6.15 The Theory of Beta-Decay

It has already been mentioned that β-particles emitted from nuclei show a continuous energy distribution. Such an energy distribution is illustrated in figure 6–16 for β-particles emitted by

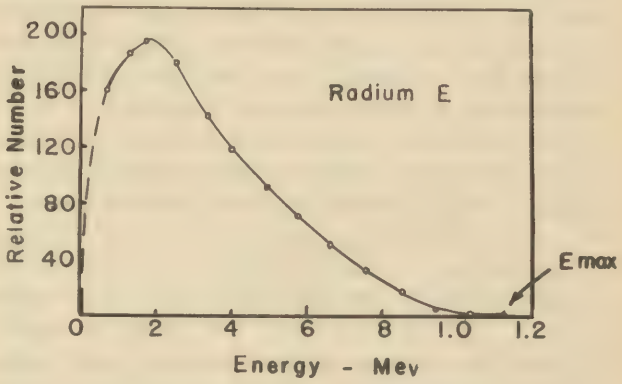

FIGURE 6–16.—Energy distribution of beta particles.

RaE. Other β-emitters show similar continuous spectra, except that each has a characteristic value of E_{max} which is sometimes called the *end point energy*. This is the value usually given in tables of β-particle energies. Experiments have shown that β-decay involves only one β-particle per nuclear disintegration.

Any attempt to explain the emission of β-particles from the nucleus with a continuous energy distribution must satisfactorily explain not only the end point energy E_{max} but it must also account for the half-life of the decay process and predict the general form of the energy distribution curve. If one were to assume that the process of β-decay is similar to that of α-decay, then one would have monoenergetic β-particles or groups of such particles leaving the nuclei. One might conceivably argue that such is the case and that these monoenergetic particles are converted into a continuous spectrum of rays by losing energy outside the nucleus by interaction with the orbital electrons. However, it can be demonstrated

that such a conversion to a continuous spectrum is not possible.

It is inconsistent with our knowledge of modern physics to postulate the existence of electrons within the nucleus prior to decay. In the case of α-emission, this was not true, for it was shown that the saturation character of nuclear forces leads to a stable configuration of two neutrons and two protons which can be tolerated within the nucleus. How then can one reconcile the emission of β-particles from the nucleus, if they are not allowed to exist there? One must assume that when β-decay occurs, the electron is created and leaves the nucleus. Thus the β-particles would have the same type of virtual existence within the nucleus as does the X-ray photon in the atom prior to its emission therefrom.

One conceives of the nuclear process whereby β-particles are created as being a break-up of a nuclear neutron into a proton and an electron.

$$ {}_0n^1 \rightarrow {}_1p^1 + {}_{-1}e^0 \qquad (22) $$

Such a creation process is indicated in the subnuclear reaction equation. In such a reaction the electron is assumed to have negligible mass. Since this reaction leaves the resulting nucleus with an additional $+1$ charge, it satisfies the requirement that β-decay changes the parent nucleus into a daughter with an increased nuclear charge of 1.

Even with such a creation process, there is still the difficulty of explaining the continuous energy spectrum of the β-particles. The assumption that the β-particle originates from the subnuclear conversion of a neutron into a proton explains the existence of the electron but fails to endow it with a continouus energy distribution. Supposing that a β-particle of any energy E_1 is emitted by a nucleus whose β-particle upper energy limit is E_{max}. This is illustrated diagramatically in figure 6–17. Then the β-particle carries away from the nucleus energy equal to E_1. It must be assumed that each β-decay process releases energy equal to E_{max} and therefore it is clear that an amount of energy $E=E_{max}-E_1$ is unexplained. Now one can perhaps question whether or not both energy and momentum are conserved in the process of β-decay, but the conservation laws are so all embracing in their range of validity that it is difficult to assume that the

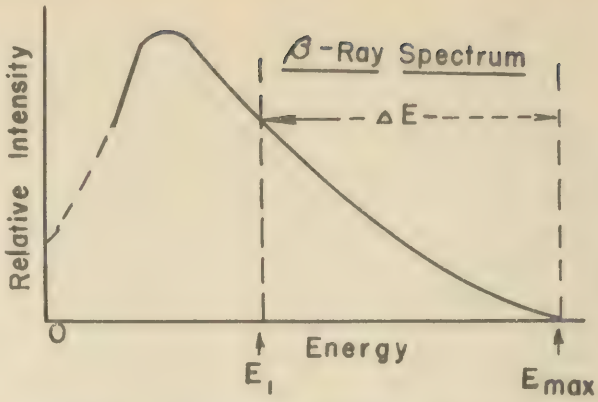

FIGURE 6–17.—Energy relations in beta emission.

laws do not apply here. As an alternative hypothesis, the theoretical physicist, Pauli, suggested that a new type of particle, *the neutrino*, is involved in the β-decay mechanism. He assumed that the neutrino is a fundamental particle of very small mass and electrically neutral. When the β-particle is created, a neutrino is simultaneously produced and carries away the energy ΔE which is not given to the β-particle. Thus the creation equation, Eq. (22) should be rewritten as:

$$ {}_0n^1 \rightarrow {}_1p^1 + {}_1e^0 + {}_0\eta^0 \qquad (23) $$

where ${}_0\eta^0$ is the symbol for the neutrino.

By virtue of its peculiar properties, no charge and practically zero mass, the neutrino is an extremely elusive particle, and the chief evidence for its existence is theoretical in nature.[1]

Two theories of β-decay have received most attention from the scientific world. One was proposed by Enrico Fermi and the other by Konopinski and Uhlenbeck. Both theories predict continuous β-particle spectra which agree fairly well with observations. Fermi has deduced that the maximum energy E_{max} emitted in β-decay is related to the decay constant by the following equation:

$$ \lambda = k E_{max}^5 \qquad (24) $$

where the constant k has slightly different values for different nuclei. This equation is often called the Fermi relation. Sargent had found the same relation empirically prior to its deduction on a theoretical basis. A plot of $\log E_{max}$ against

[1] Certain experiments have been reported which give about the best experimental indication for the existence of neutrinos. The reader is referred to a paper by H. R. Crane and J. Halpern, "Physical Review" *53*, 789 (1938).

log λ where λ is the disintegration constant for β-decay, is called a Sargent diagram and is shown in figure 6–18.

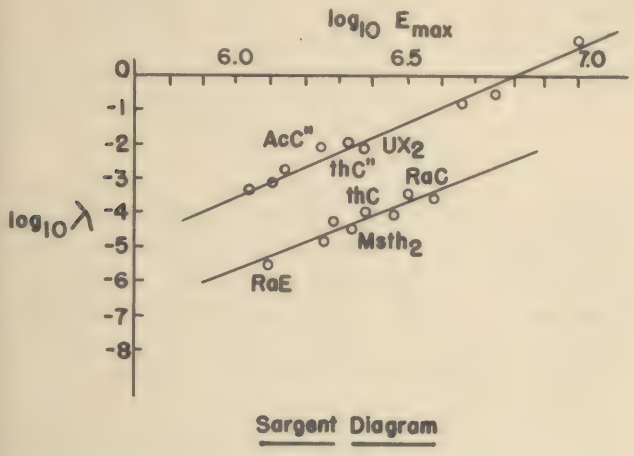

FIGURE 6–18.—A Sargent diagram.

6.16 The Absorption of β-Particles

Beta particles are far more penetrating than α-particles. While our discussion of α-particle absorption was limited principally to gases, the following discussion will be concerned both with gases and solids. Whereas an α-particle of several Mev energy has a specific ionization of several thousand ion pairs per centimeter of air, a β-particle of the same energy produces only a few ion pairs per cm. One reason for this is that for the same energy, say 3 Mev, a β-particle travels with about 99 percent the speed of light c, while an α-particle of the same energy has a velocity of only 4 or 5 percent of c. It is therefore necessary to examine phenomena of β-particle absorption in detail just as was done in the case of α-particle absorption.

(*a*) *Interaction of β-particles with matter.*—In dealing with the absorption of β-radiation from a pure β-emitter where a continuous spectrum is involved, it is apparent that the problem of relating range to energy will not be as simple as it was for α-particles. Furthermore, cloud chamber pictures of β-particles show they do not travel in straight lines as do alphas but rather they are subject to many deflections and as a result, the β-particles may pursue a more or less tortuous, random path. When combined these effects yield an absorption curve which looks somewhat like an exponential curve (see subsec. (*b*)). Before presenting range versus energy curves, it is advantageous to discuss the mechanism by which electrons are slowed down in passing through matter.

When a high energy electron passes close to a nucleus and interacts with the nuclear field, it undergoes acceleration. The laws of electrodynamics require that an electric charge radiate energy when it is accelerated. Thus when the electron makes such a "virtual" collision with a nucleus, it radiates a quantum of energy. This quantum will be emitted with a frequency which depends upon the energy of the incident β-particles and upon the closeness of the collision. Such processes are known as *radiative collisions* and also as *bremsstrahlung* processes. The latter term is a German word meaning "braking radiation." When a β-particle makes a similar collision with an orbital electron, it does not undergo a similar reaction. However, at much higher energies ($>10^7$ev.) β-particles do react with orbital electrons in directed collisions and transfer most of their energy into what are called knock-on electrons. Such processes need not enter into consideration here.

For lower energies, the β-particle loses energy by the conventional process of ionization (collision loss). In this process, as was the case for α-particle ionization, the electric field of the β-particle pulls electrons from their shells, thus causing ionization. It can be shown that the ionization loss which atoms suffer in this way depends upon the square of the charge which the incident particle carries. Thus an α-particle has four times the ionizing power of a β-particle of the same velocity.

In general, radiative losses suffered by electrons are less than ordinary collision losses. For higher energies and heavier elements, the radiative process becomes more important in absorbing electrons.

The deflection or elastic scattering of electrons is important for many nuclear experiments. It is found that in traversing a thickness t of an element of atomic number Z, the angle through which the electron is deflected away from its original path varies as the square root of t, and for any scattering angle, the intensity is proportional to Z^2. Elastic scattering occurs as a result of β-particles interacting with nuclei as well as with orbital electrons. In materials of very low atomic number, elastic scattering is roughly the same for

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both processes, whereas for heavy elements nuclear scattering is by far the more important process, often 100 times as large. Elastic scattering should not be confused with the radiative collision process which is an inelastic scattering taking place at high energy.

(*b*) *Range of β-particles in matter.*—The range in air of β-particles may be plotted as a function of energy, just as was done for α-particles. Such a plot is given in figure 6–19.

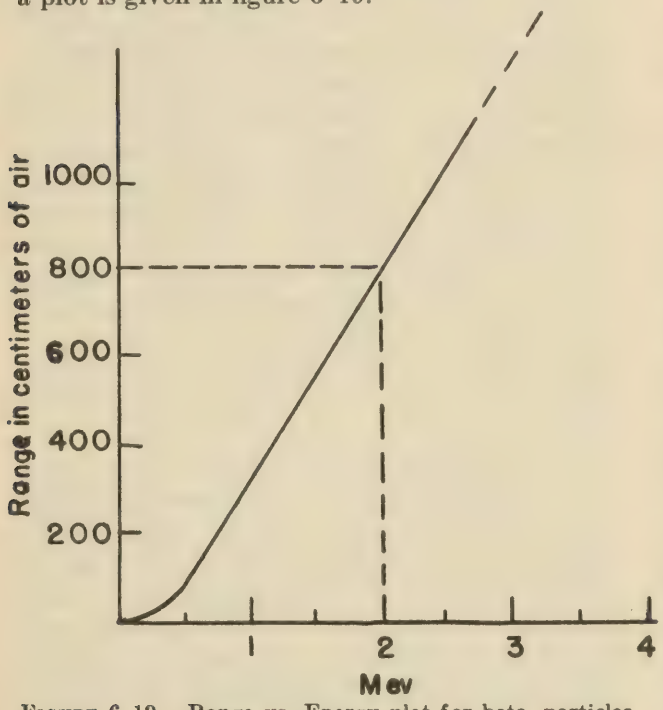

FIGURE 6–19.—Range vs. Energy plot for beta particles in air.

Thus a β-particle having an energy of 2 Mev has a range of over 8 meters in normal air. Since β-particle absorption is independent of the material of the absorber, it is customary to express the range in grams/cm² of the absorbent. Figure 6–20 gives the range-energy plot where the range is expressed in gm/cm². At low energies the ionization losses and elastic scattering are very large, and the curve departs from the linearity which is exhibited at higher energies.

A typical absorption curve for primary β-emission is given in figure 6–21. The word *primary* will be used for β-particles of continuous energy distribution. The intensity falls off sharply for small thicknesses of absorber, since the low energy β-particles are rapidly absorbed. Thereafter, the

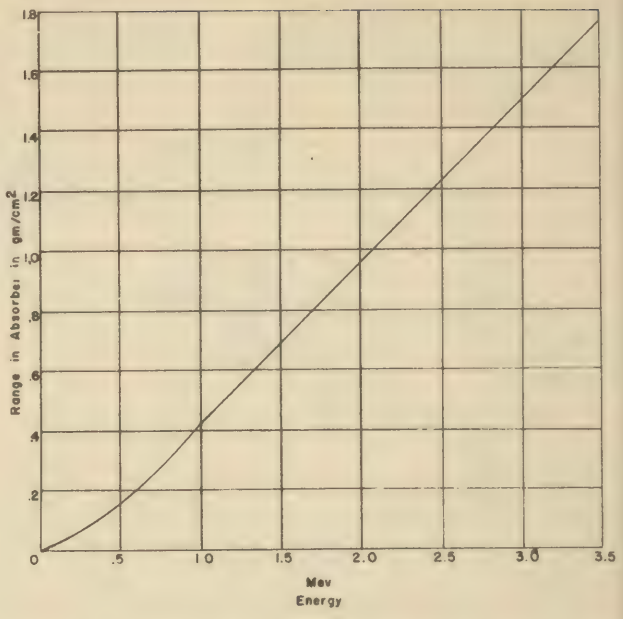

FIGURE 6–20.—Range vs. Energy plot for beta particles.

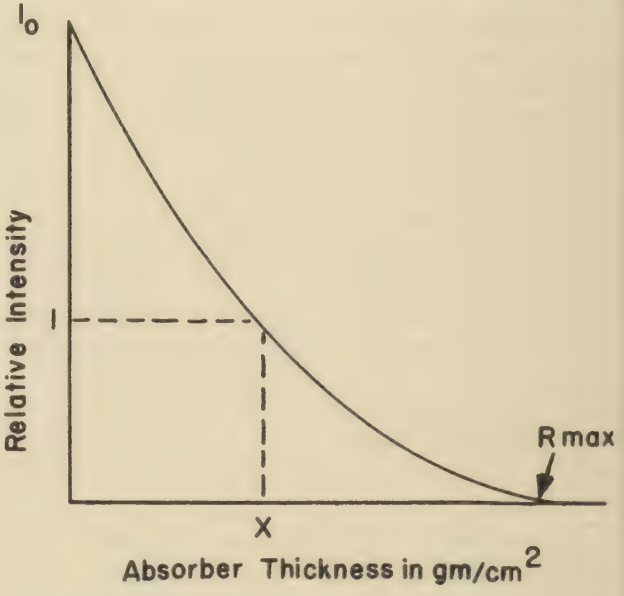

FIGURE 6–21.—A typical absorption curve for primary beta particles.

curve is fairly well represented by the exponential $I = I_0 e^{-\mu x}$, where μ is the linear absorption coefficient. If the absorber has a density $= \rho$ then the quantity $\mu_m = \mu/\rho$ is called the mass absorption coefficient. This coefficient μ_m is roughly independent of the atomic number Z of the absorbing element. Actually μ_m increases slightly with larger values of Z, but for practical

purposes it may be regarded as a constant. The point on the abscissa of figure 6–21 corresponding to zero intensity is called the *maximum range* of the β-particle and is an important experimental quantity. A rough estimate of the absorbing thickness or range of β-particles in any material may be obtained from the formula:

$$t\rho = R = 0.54E_m - 0.16$$

where t is the thickness of the absorbing material in centimeters, ρ the density of the substance in grams per cubic centimeter, and E_m the maximum energy of the β-particles in Mev. These units yield the range R in grams per square centimeter. For a situation where β-particles of two energies exist, we may treat each group as having its own maximum energy and add the results, or even obtain a practical average by treating the particles as if they had one maximum which is the average energy of the two most energetic groups.

(*c*) *β-particle spectra.*—The general form of the continuous or pure β-particle spectrum has already been discussed in section 6.15. However, there are, in addition to the primary β-particles, discrete β-particles which are emitted from electronic shells of atoms, the nuclei of which emit γ-rays. These secondary β-particles thus constitute the line-spectra. In some atoms which emit primary and discrete β-particles, the number of secondary rays is small compared with the primaries. There are, on the other hand, some isotopes which give off more secondary than primary β-particles. Since the secondary β-particles derive their energy from a photoelectric process, their energies are characteristic of the atoms from which they are emitted.

6.17 Nuclear Gamma Rays

(*a*) *The origin of gamma rays.*—In the case of line spectra in the optical region, it was shown that the existence of discrete emission line spectra implied that the atom itself contained discrete energy levels, transitions between which gave rise to photons of energy equal to the difference in energy between the levels. For the case of the nuclear system, two different line spectra are known to be emitted: the α-particle and the γ-ray spectra.

When α-particle spectra were discussed, no mention was made of the explanation for the existence of groups of α-particles having discrete energies. This subject is discussed at this point in order to show the relation between α-particle and γ-ray line spectra. Assume that an α-emitting nucleus gives off several discrete groups of α-particles, called α_0, α_1, α_2, and so forth. These correspond to discrete energy levels within the nucleus. Such levels are diagrammatically illustrated in figure 6–22 where they are superposed on a potential energy curve for the nucleus.

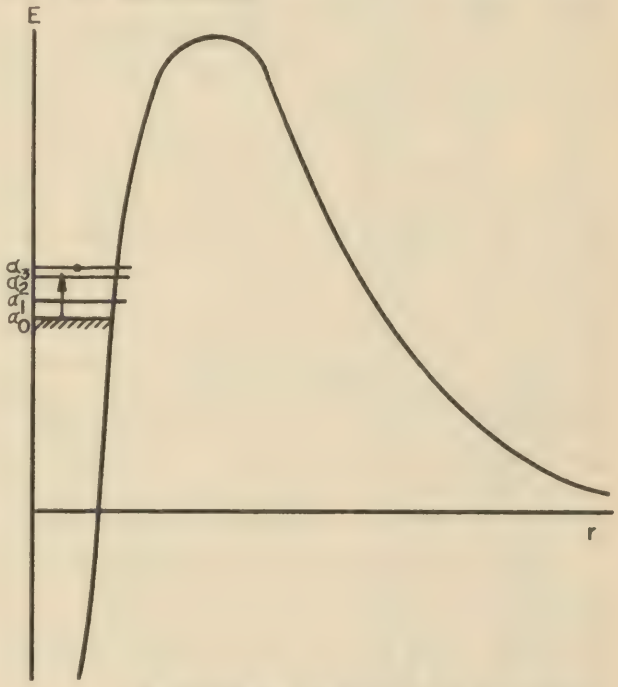

FIGURE 6–22.—Nuclear energy level picture.

When an α-particle is emitted from a nucleus, it need not necessarily leave that nucleus (which is now the daughter) in its ground state. Instead it may leave it in an excited state. The daughter nucleus may then drop down to its ground state by emitting a γ-ray. Another possibility exists—the daughter nucleus may jump directly from its excited state by emitting an extra high energy α-particle and going to the ground state of its daughter (this would be the granddaughter of the original parent). In this case, where there are two possible processes, a competition occurs, and that with the shortest mean life will predominate. Nuclei will decay by two different schemes, for example, RaC′, ThC′, and AcC′ (see fig. 6–6). These are called *isomers*, and the phenomenon is

itself called *nuclear isomerism.* These two processes can be stated as follows: Let

E_α be the energy of the emitted α-particle.

E_D be the normal energy for the disintegration process.

Case I; $E_\alpha > E$: In this case the α-particle has extra energy which must be attributed to the parent nucleus having been left in an excited state when it was formed. As an example, β decay of RaC leaves RaC′ in an excited state. In the subsequent transition by α decay to RaD, the α carries away this extra energy.

Case II; $E_\alpha < E$: Here the α-particle has less than normal energy, which must be due to the product nucleus (daughter) being left in an excited state. Thus in the transition from ThC to ThC″, α-particles are emitted to take the excited ThC″ nucleus to its ground state. Figure 6–23 shows an energy level scheme for ThB, ThC, ThC′, ThC″, and ThD as well as the α, β, and γ-transitions which take place between these levels. For the purpose of this discussion, the lowest level of ThD is taken equal to zero energy. All other energy levels are plotted on a linear scale above this zero level. Not all conceivable transitions are shown on this diagram. The reason for this is that certain transitions are forbidden by quantum mechanics. There are operative within the nucleus a set of selection rules which determine whether or not a given transition will occur. A discussion of this subject involves factors other than those which will be considered in this simplified treatment of nuclear physics.

(*b*) *Gamma ray spectra.*—One might wonder how line spectra of γ-rays could be obtained experimentally, for the rays themselves are not subject to deflection in an electric or a magnetic field. γ-rays energies may be measured by measuring internally converted electrons for low energy γ-rays and by observing Compton electrons and photo-electrons for higher energy gammas.

It will be seen from figure 6–23 that γ-ray spectra are associated with both α and β emission. As a general rule, γ-rays are more often associated with β-particles—these gammas are usually also harder than those found accompanying α-emission A radioactive isotope which emits β-particles unaccompanied by γ-rays is called a pure β-emitter.

(*c*) *Absorption of γ-rays.*—The mechanism of the interaction between gamma quanta and matter has already been discussed for X-ray quanta and it need not be repeated here. A γ-ray photon differs from both β- and α-particles in that it does not produce an ion track such as could be photographed in a Wilson Cloud chamber.

Two types of absorption coefficients for γ-rays have been introduced thus far, namely, the linear absorption coefficient μ, and the mass absorption coefficient $\mu_m = \mu/\rho$. It is instructive to introduce two more coefficients, that is, the atomic absorption coefficient, μ_a and the electronic absorption coefficient, μ_e.

$\mu_a = \frac{\mu_m}{N}$ relative absorption per atom (since N=number of atoms per gm)

$\mu_e = \frac{\mu_a}{Z}$ relative absorption per electron (since there are Z electrons per atom)

In table IV, values of these four coefficients have been tabulated for representative elements. These coefficients all refer to a γ-ray energy of 1.3 Mev.

TABLE IV

Element	μ (cm^{-1})	$\mu_m = \mu/\rho$ (cm^2/gm)	$\mu_a = \mu/\rho N$ (cm^2/gm/atom)	$\mu_e = \mu/\rho NZ$ (cm^2/gm/electron)
Carbon	0.12	0.06	1.2×10^{-24}	2.0×10^{-25}
Aluminum	.16	.06	2.6×10^{-24}	2.0×10^{-25}
Iron	.46	.06	5.3×10^{-23}	2.1×10^{-25}
Copper	.51	.06	6.1×10^{-23}	2.1×10^{-25}
Tin	.35	.06	1.2×10^{-22}	2.4×10^{-25}
Lead	.80	.07	2.5×10^{-22}	3.0×10^{-25}

On the assumption that the γ-rays interact only with electrons, it might be thought that for γ-rays of the same energy the quantity μ_e would be the same for all elements. The fact that μ_e (column 4 in the table) increases for lead to a value 50 percent higher than that for the light elements demonstrates that the binding energy of the electron comes into consideration. Thus more tightly bound electrons, which are present in heavier elements, absorb relatively more energy per electron than do the more loosely bound ones.

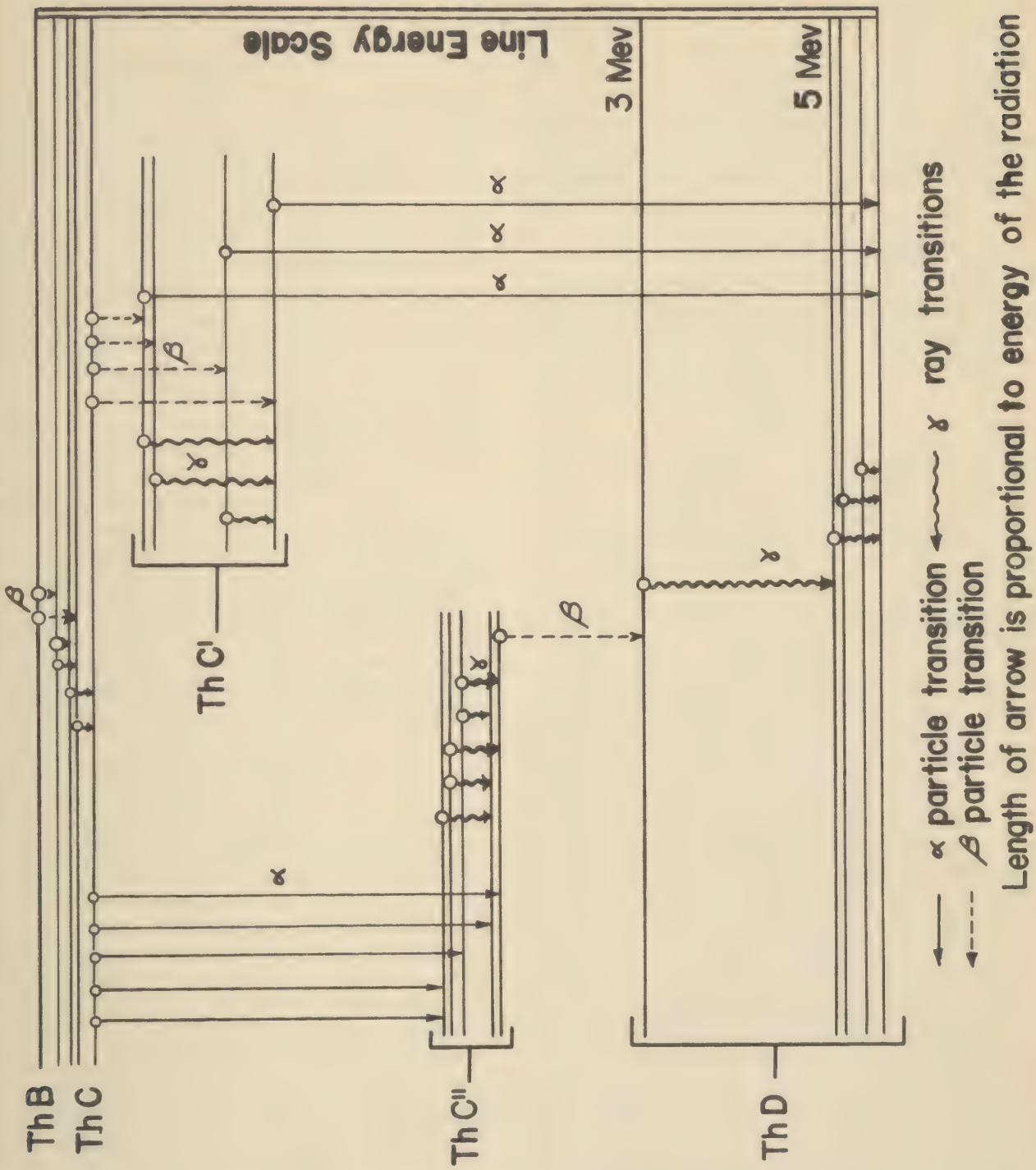

FIGURE 6–23.—Energy level scheme for thorium B, C, C^{1}, C^{11}, and D.

Chapter 7
NUCLEAR REACTIONS

7.01 Nuclear Bombardment

It is well known that two nuclear particles strongly resist any effort made to bring them close together. Because of the high potential barriers which exist in nuclei, an incident particle must have a very high velocity before it can overcome the potential barriers. This is the reason why nuclear reactions, more properly designated as *induced reactions*, are so rare under ordinary circumstances. For example, molecules of air at room temperature have an average energy of about 1/30 e. v., and atoms involved in chemical reactions rarely exchange more than a few e. v. of energy. Since such energies are small compared with the heights of nuclear potential barriers, the particles never come close enough to cause a nuclear reaction to be induced.

In describing experiments in which induced nuclear disintegrations occur as the result of nuclear bombardment, it is customary to use the heavier of the two participating nuclei as the target, and to use the lighter particle as the missile which is projected at the target. Nuclear missiles commonly used include all elementary particles, which can be accelerated to high velocity by some device called an *accelerator*. A few of the more generally used particle accelerators will be described in the following sections.

Since natural radioactivity furnishes a simple source of high-energy particles, it is quite understandable that the earliest experiments in the field of induced radioactivity were performed with this source. Shortly after Rutherford's early work in this field, physicists took advantage of another natural source of high-velocity particles, namely the cosmic radiation, to observe new types of reactions. Cockroft and Walton then demonstrated that protons could be artificially accelerated, and a new type of nuclear research was born. This field led to the development of the huge particle accelerators, such as the cyclotrons, betatrons, and Van de Graf accelerators, which are in vogue today.

Researches in the field of induced radioactivity have led to the discovery of many artificially produced radioisotopes and have produced a very large number of new types of nuclear reactions. What is more important from the standpoint of atomic energy, the experiments in nuclear disintegration have resulted in the discovery of a new particle called the neutron.

7.02 Rutherford's Alpha Particle Bombardment

Lord Rutherford first showed in the year 1919 that bombardment of nuclei with α-particles could produce nuclear disintegrations. The apparatus which he used to observe this important phenomenon is sketched in figure 7–1.

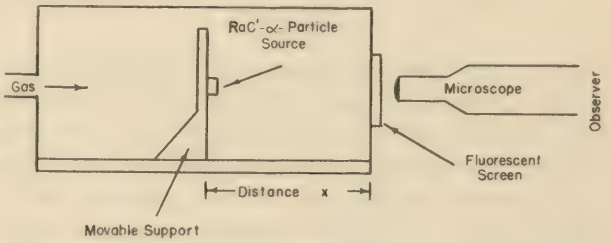

FIGURE 7–1. Rutherford's alpha particle bombardment experiment.

In this experiment a RaC′ source is used. It is mounted on a moveable platform and placed within a gas-tight container, one end of which supports a zinc sulphide screen. Zinc sulphide has the property of giving off scintillations of visible light when bombarded by heavy, charged particles. An observer who has thoroughly adapted his eyes to a darkened room can use a microscope and observe the scintillations on the screen. When the source is at a distance x, less than the range of RaC′ α-particles, the ZnS screen is illuminated with many scintillations. However, with the chamber of the apparatus filled with nitrogen, Rutherford and Chadwick found that some scintillations were observable on the screen even when the source was at a distance much greater than 7 cms. (the range of RaC′ α-particles). It was felt that these scintillations were caused by long range protons produced as a result of the disintegration of nitrogen nuclei. The protons were attributed to a nuclear reaction given by the equation:

$$_7N^{14} + _2He^4 \longrightarrow _8O^{17} + _1H^1 \qquad (1)$$

Many years later, cloud chamber pictures were taken which demonstrate graphically how the reaction takes place. Figure 7–2 shows a diagram of a single $_7N^{14}$ disintegration under α-particle bombardment.

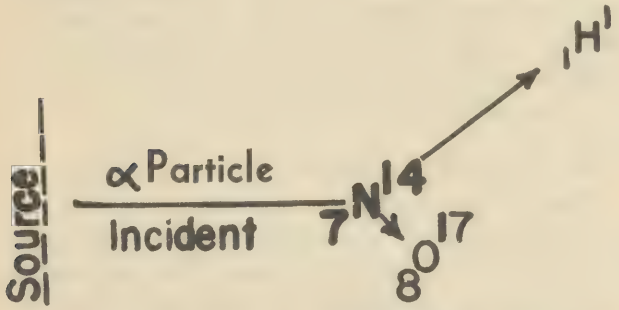

FIGURE 7–2.—Nitrogen disintegration by alpha bombardment.

The short track corresponding to $_8O^{17}$ is usually called a *recoil track*, and the $_8O^{17}$ is in this case a *recoil nucleus*. By the application of the conservation laws of energy and momentum, the angles which the disintegration products make with the direction of the incident particle may be easily calculated and coincide with observed values.

Further studies by Rutherford and others showed that protons produced by the transmutations of nitrogen are emitted uniformly in all directions. Furthermore, other elements which were examined for transmutation were observed to emit protons. Most of the light elements disintegrate under α-bombardment, yielding protons. Of these, aluminum, nitrogen, and boron exhibit the highest probability for reactions of this (α, p) type. This terminology (α, p), is quite generally used; the incident particle is always the first within the parentheses and the resulting emitted particle is second.

In the case of α-emission from nuclei, it was pointed out that classical concepts did not allow α-particles to escape from the confines of the nuclear potential barrier. Just as the potential barrier (on the classical picture) trapped particles within the nucleus, in the same way particles bombarding nuclei are forbidden entrance into these nuclei unless they have kinetic energy sufficient to pass over the potential barrier. An analysis of the problem of α-bombardment of certain light nuclei shows that the energy of the natural α-particles from, say, *RaC'* is less than the height of the potential barrier and therefore no disintegrations should occur. This difficulty is solved by the wave mechanical theory, which allows for a penetration or "tunneling" through the potential barrier. It is for this reason that nuclear reactions can be initiated at energies which may be much lower than the potential barrier maximum.

7.03 Nuclear Cross Sections

In the process of passing through matter a high speed α-particle may actually traverse about 10^5 atoms before it is absorbed. From Rutherford's experiments, it can be shown that only about 1 α-particle in every 10^5 emitted causes a nuclear transmutation. Thus only about 1 collision in 10^{10} results in an (α, p) reaction. At best, then, these reactions are very improbable.

Obviously, some consistent manner of expressing the probability for the occurrence of a given reaction is needed. In other words, there is required a means of expressing this probability in numerical form. One way to approach this problem is to imagine a uniform beam of particles striking a target, as shown in figure 7–3. Let

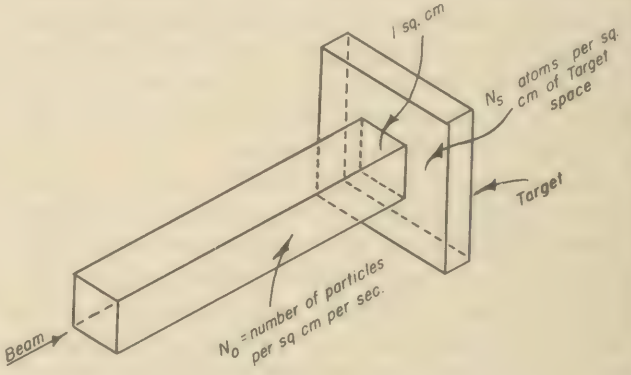

FIGURE 7–3.—The concept of nuclear cross section.

N_0=number of incident particles per sec. per cm^2 of target area.

N_s=number of atoms per cm^2 of target area.

N_r=number of reacting particles per sec. per cm^2 of target area.

Sigma (σ)=a quantity, *cross section* expressing the probability for a specific reaction to occur.

Thus:

$$\sigma = \frac{N_r}{N_0 N_s} = \frac{(Cm^{-2})(Sec^{-1})}{(Cm^{-2})(Sec^{-1})(Cm^{-2})} = Cm^2 \quad (2)$$

Thus it is as though each atom on the target presented an *area* σ, to the bombarding particle for the given reaction to occur. It will be shown that there are many types of nuclear disintegrations, and for some of these the cross section is rather high—in some cases as large as 10^{-20} cm^2. Other reactions are very improbable and yield cross sections as low as 10^{-32} cm^2. In fact, the variation in cross section is so extreme that it is sometimes difficult to visualize it in comparison with the physical cross sectional area of a nucleus, i. e., 3×10^{-24} to 3×10^{-25} cm^2. A convenient unit for measuring cross section is the *barn* (10^{-24} cm^2).

7.04 The Discovery of the Neutron

The alpha bombardment of light elements also showed that short wave electromagnetic radiation is produced and has the same properties as do the γ-rays emitted by naturally radioactive substances. When the element beryllium was bombarded with α-particles, a strange unexplained effect took place. Instead of protons, a very penetrating radiation was emitted which was thought to be a very short wave length γ-ray. Absorption measurements made by Bothe indicated these rays had absorption coefficients corresponding to energies in the neighborhood of 15 Mev.

What was most unusual about this penetrating radiation was that when it was allowed to fall upon a paraffin slab, it apparently produced a new type of radiation having a very long range, i. e., over 20 cms. of air. The English physicist Chadwick first showed that the penetrating rays emitted by the Ra-Be source could not be γ-rays. Chadwick investigated the particles ejected from the paraffin and proved that they were protons. He then showed that the rays emitted by the Ra-Be source must be neutral particles having about the same mass as protons. These particles he called *neutrons*.

It is easy to see that neutrons should transfer a maximum amount of energy to protons in passing through a hydrogen-rich material such as paraffin. In any elastic collision, if the colliding substances are of about equal mass, the energy transferred from the incident object to the recoil object will be maximal. In this way, high energy protons are produced in the paraffin by neutron impact. The reaction equation for neutron production is written:

$$_4Be^9 + {}_2He^4 \longrightarrow {}_6C^{12} + {}_0n^1 + Q \quad (3)$$

Since the masses of Be, He, and C are known, and since the initial energy of the α-particle is also known, the measurment of the "Q" of the reaction allows for a measurement of the mass of the neutron to be made. Measuring the "Q" of the reaction requires that the energies carried off by the disintegration products, ${}_6C^{12}$ and ${}_0n^1$, must be evaluated. This can be done experimentally. For a precise measurement of the neutron mass, another type of reaction is preferable. This reaction, the photo-disintegration of the deuteron nucleus, will be described in section 7.12.

Neutrons may also be produced by the α-bombardment of other light elements, but the α-particle bombardment of beryllium is one of the reactions yielding neutrons in greatest abundance. Three types of such sources are generally used:

1. *Ra-Be source*—2. *Rn-Be source.*—The radium beryllium and radon beryllium sources yield about 10 to 15×10^6 neutrons/sec for each curie of α-radiation in the source. Recently, powdered radium beryllium mixtures have been prepared in a pressed form which yield 1.7×10^7 neutrons/sec/gm *Ra* for high *Be* to *Ra* mass ratios.

3. *Po-Be source.*—This source yields about 2.8×10^6 neutrons/sec/curie.

The energies carried off by neutrons from any of these sources vary, but for the Ra-Be mixture, neutrons are emitted with energies up to 13 Mev. Such neutrons are called *fast neutrons*.

7.05 Artificial Radioactivity

Joliot and Curie investigated the alpha induced neutron emission in a number of light elements, and discovered that some of these elements were made radioactive by the bombardment with α-particles. That is to say, the elements continued to undergo disintegration long after they had been removed from the vicinity of the α-particle source. Prior to their work, all nuclear reactions which had been produced in the laboratory had been instantaneous and ceased just as soon as the bombardment was stopped.

Elements such as Al, Si, and P were found to decay by emitting positrons. The process can be best understood by considering the production of radiophosphorous which was the first artificial radioisotope made by Curie and Joliot in 1934. The two step reaction is:

$$_{13}Al^{27} + _{2}He^{4} \longrightarrow _{15}P^{30} + _{0}n^{1} \qquad (4)$$

$$_{15}P^{30} \xrightarrow{2.3m} _{14}Si^{30} + _{1}e^{0} \qquad (5)$$

The first equation describes the usual neutron production reaction. Here $_{15}P^{30}$ is a disintegration product which is unstable and decays with a half life of 2.3 minutes into $_{14}Si^{30}$ and a positron. Positrons, as emitted by radioisotopes, are exactly the same as the cosmic ray particles, bearing +1 charge and having a mass equal to that of the ordinary negative electron. Absorption experiments showed that the positrons are stopped in matter in the same manner as ordinary β-particles.

As a general rule, it can be stated that the cross section for producing an artificial radioisotope varies inversely as the half life of the isotope. In effect, this means that it is easier (requires fewer bombarding particles) to induce artificial radioactivity having a short half life than it is to do so for isotopes of longer half life. Today every element in the periodic system has at least one radioisotope and about 450 induced radioactivities are known. Some of these, such as C^{14}, P^{32}, and I^{131}, are well known for their application to medical research and therapy.

It is now known that artificial radioactivity can be induced by many reactions other than those produced by alpha bombardment. The use of natural radioisotopes, such as RaC and Po, seriously limits the experimenter to alpha, beta, and gamma-rays of rather limited energy and intensity. It was for this reason that Cockcroft and Walton's experiment with the acceleration of protons is of such significance for it opens up a whole new field of nuclear physics to investigation.

7.06 The Cockcroft-Walton Experiment

In 1932, Cockcroft and Walton managed to produce an artificially accelerated beam of protons with an energy of about 150,000 ev. They directed this beam at a lithium target and observed the emitted α-particles. The nuclear reaction initiated by the 0.15 Mev protons is:

$$_{3}Li^{7} + _{1}H^{1} \longrightarrow 2\,_{2}He^{4} + Q \qquad (6)$$

This would be the reaction occuring in the more abundant isotope of lithium. Since the energy of the protons is quite exactly known, the energy imparted to the pair of helium nuclei can be calculated as follows:

$_{3}Li^{7} = 7.01818$
$_{1}H^{1} = 1.00813$
$+$K. E. of $_{1}H^{1} = 0.00016$ (0.15 Mev = 0.00016 m.u.)
Initial mass = 8.02647
$2 \times _{2}He^{4} = 8.00778$ (2×4.00389)
$+$K. E. of $_{2}He^{4} = Q$
Final mass = $8.00778 + Q$

Equating:

$8.00778 + Q = 8.02647$
$Q = 0.1869$ m.u. excess energy
$Q = 17.4$ Mev.

The reaction thus leads to two products which have less mass than that of the original particles. The Q to this reaction is +17.4 Mev which appears in the form of kinetic energy of the two α-particles. Each α-particle will carry off 8.7 Mev energy and will have a range in air of over 8 cms. These predictions are verified experimentally and show that the above system of mass-energy accounting is a valid one.

In solving the above example, the values used for nuclear masses are actually atomic mass values, but this does not affect the validity of the results. The reason why this can be done is that the same number of electrons are present on both sides of the equation and thus balance out. This method works for all reactions excepting positron emission, where the decaying isotope loses not only a positron but also an orbital electron. This is taken into account by adding two electron masses (or 1.02 Mev) to the mass of the disintegration product.

Now a particle emitted by a natural radioisotope with, say, an energy of 5 Mev, should be identical with a particle of the same type which is accelerated to an energy of 5 Mev by some machine. Therefore, the remarkable aspect of the Cockroft-Walton experiment is not that laboratory

accelerated particles could initiate nuclear disintegrations, but that these particles could cause such reactions at such low energies as 150,000 e.v. These findings prompted physicists the world over to try to devise new types of accelerators or atom smashers which would accelerate other types of particles to even higher energies. The original equipment built by Cockroft and Walton consisted of an accelerating tube with a hydrogen arc source. To this tube they applied a high potential which was obtained through a high voltage transformer and a special arrangement of rectifiers and condensers which served to "double" the transformer output voltage. The protons produced in the hydrogen arc were accelerated down the tube and directed against a target assembly where the nuclear reactions took place.

High voltages can be produced by:

Impulse generators (charging condensers in parallel and discharging in series)—3 Mev.

Electrostatic generators (Van de Graaf machines)—5 Mev.

Voltage multiplier circuits (arrangements of condensers and rectifiers designed to multiply a transformer output voltage)—2 Mev.

Cascade transformers (use of a series of insulated transformers yields 1 Mev.)

Resonant transformers (involves a Tesla-type design and can be used up to 2 Mev) Coils of a transformer are tuned to resonance at a relatively high frequency.

Linear resonance accelerators (Sloane-Lawrence type use of cylindrical segments aligned in a tube, each segment being of such length that the application of high frequency high voltage to segments gives continual acceleration down the tube. Voltages are limited only by length of tube and ability to maintain a beam.

Magnetic resonance accelerators (cyclotron, betatron, and synchrotron).

7.07 Particle Accelerators

Three of the various types of accelerators will be discussed briefly.

Simple accelerator.—A very simple accelerating device consists of an insulating tube inside of which are arranged cylindrical metal tubes as illustrated in figure 7–4. At one end an arc or filament source S produces ions (protons) which are injected into the main acceleration tube T by means of a focussing system F. Once injected into the chamber, the ions are gradually accelerated in successive jumps by high voltages which are placed upon the inner metal cylinders.

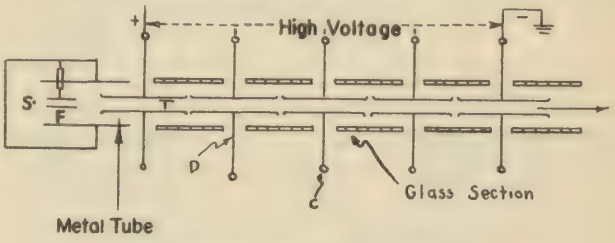

FIGURE 7–4.—The linear accelerator.

On each of the metal cylinders there is imposed a progressively higher voltage from a direct current external supply. These cylinders are insulated from each other by segments of the external glass or porcelain tube. The whole system is maintained under a high vacuum (10^{-5} mm. Hg) by high-speed pumps. With the high vacuum the particles being accelerated do not suffer energy loss by collisions with gas molecules, and a gas discharge inside the accelerating tube is prevented. The use of many separate acceleration cylinders and corona discharge rings allows a uniform potential gradient over the length of the tube. Thus the ions are focussed into a narrow beam of several Mev energy and directed against a target assembly (not shown) where they give rise to nuclear reactions.

The cyclotron.—In 1932, Lawrence developed a very novel technique for accelerating particles to high energies without using very high DC voltage sources. This device, called a cyclotron, operates on the following principles. Figure 7–5 shows a diagram of the essential components of a cyclotron. The acceleration chamber is a hollow metal pillbox consisting of two semicylindrical dees which are insulated from each other. The dee system is attached to a vacuum pump and kept under a high vacuum and is sandwiched between the poles of a large electromagnet. To each of the dees there is applied a high frequency voltage of about 10 megacycles/sec.

At the center of the dee system is an arc source for producing positive ions. These ions are accelerated into one of the dees, say D_2, by the potential difference existing between D_1 and D_2.

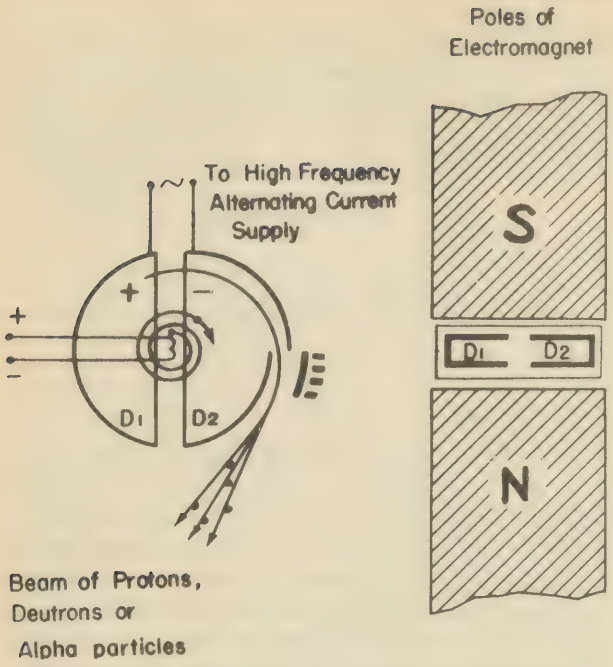

FIGURE 7–5.—Principal components of a cyclotron.

This potential difference arises from the fact that D_1 is at a positive peak while D_2 is at a negative peak of the voltage cycle. Thus the ions are accelerated into D_1 where they enter into a field free space since the electric field exists only between the dees. However, the effect of the uniform magnetic field is to cause the ions to move in circles. As the ions make a 180° trip through D_2, they again enter the space between the dees where they are accelerated once more. This time when they enter D_1, the ions have more kinetic energy and hence are less affected by the magnetic field. Therefore, as the ions make more complete circles in the dees, they spiral out into circles of larger radii. Since the centripetal force on the particle must equal the force of the magnetic field,

$$Hev=\frac{mv^2}{r} \tag{7}$$

where

H=magnetic field in oersteds
e=charge of particle being accelerated
v=velocity of the particle
m=mass of the particle
r=radius of the particle path

Thus the radius in which the particle will move is:

$$r=\frac{mv}{He} \tag{8}$$

For proper acceleration in the cyclotron, the frequency of the electric field must be adjusted so that as the particles leave the dees they are in phase with the electric field and are accelerated across the space between the dees. This condition is met by making the angular velocity of the high frequency field equal to the angular velocity of the ions. Thus:

$$\frac{v}{r}=2\pi f \tag{9}$$

Substituting the value of v/r from Eq. (8), it is found that

$$f=\frac{He}{2\pi m} \tag{10}$$

where f is the frequency of the oscillator in cycles/sec.

Actually, the time which any particle spends in a dee is independent of the radius of the circular path it follows. It is easily shown that the energy of an ion traveling at radius r in field of value H is given by:

$$E=\frac{e}{200m}(Hr)^2 \tag{11}$$

where E is given in Mev.

As an example, protons running on a 16 cm. radius in a magnetic field of 13,000 oersteds attain an energy of 2 Mev. Insertion of a deflecting plate allows the particles to be brought out of the chamber through a thin window. This deflecting plate carries a high voltage in order to pull the particles from their paths. Once the beam leaves the dees and the magnetic field, it travels in a straight line away from the cyclotron. Bombardments of targets are often carried on inside the vacuum chamber or with the outside beam.

At Berkeley, the most recently constructed cyclotron is a frequency-modulated type which overcomes the fact that the particles being accelerated increase in mass because of their high velocity and get out of phase with an ordinary type of high frequency acceleration. The new machine has accelerated deuterons to 200 Mev using this type of modulation.

The betatron.—One might think that a cyclotron could be used to accelerate electrons as well as heavy particles. However, the electrons increase in mass much more quickly and would get out of phase between the dees. This difficulty was over-

come with remarkable success by Kerst in 1941. He devised an electron induction accelerator which is better known as a betatron. In place of a high frequency electric field to accelerate the particles, the betatron uses a varying magnetic flux, which induces an accelerating electric field. The accelerated beam impinges upon an internal target and a beam of X-rays is emitted. These high energy quanta are much more penetrating than any gamma rays artificially produced. A 300 Mev betatron is being built at the University of Illinois.

7.08 Nuclear Reactions

The accelerators just described offer the possibility of producing almost any type of high energy particle for bombardment purposes. The commonly used accelerated particles are: electrons, protons, deuterons, and alpha particles. By allowing them to impinge on suitable targets, intense beams of neutrons, X-rays, and gamma rays can be obtained. There are about 280 stable nuclei in nature, any of which can be used as a target for any of the missiles mentioned above. Furthermore, for any single type of bombarding missile there may be more than one type of reaction which occurs. It is therefore readily appreciated that it would be impossible to describe even a small fraction of all reactions which are known.

Because certain of the reactions throw new light on nuclear structure a few of these will be discussed. Later in the chapter, the various nuclear reactions for producing neutrons will be described and this will furnish an indication of the variety of reactions which may occur. Nuclear disintegrations can be grouped in the following general categories which are set up on the basis of the nature of the disintegration products.

(*a*) *Simple excitation of the nucleus.*—In this case, the collision puts the nucleus in a higher state of excitation and subsequently a γ-ray is emitted, bringing the nucleus back to its ground state. Such reactions are easily induced by heavy particle bombardment of light elements.

Example: *Alpha-gamma reaction.*—The general case of gamma emission by alpha-particle bombardment of a nucleus with simple excitation is:

$$Z^A + {}_2He^4 \rightarrow {}^*Z^A + {}_2He^4$$
$$^*Z^A \rightarrow A + h\nu$$

*An excited state of the nucleus

(*b*) *Simple capture (radiative capture).*—Here the collision results in capture of the incident particle and in the production of a new isotrope. Often this simple capture process is detected by gamma emission or by the artifiicial radioactivity of the new nucleus. Two examples of this reaction are discussed in section 7.13.

(*c*) *Two particles as end products.*—In this case, the incident particle is captured with the simultaneous emission of a different particle from the resulting nucleus. As an example, consider the so-called *D* on *D* or *D–D* reaction. Here deuterons are used to bombard a deuterium target with the following result:

$$_1D^2 + {}_1D^2 \rightarrow {}_1H^1 + {}_1H^3 + Q \qquad (12)$$

This reaction yields a proton of 14.3 cm. range and a triton (a tritium nucleus) of 1.6 cm. range. From this, the *Q* of the reaction turns out to be 4 Mev. This reaction is of great interest since all the particles involved are isotopes of hydrogen. Tritium is the heaviest isotope and it is now known to be β-active, emitting very weak β-particles with a half life of about 30 years. The reaction is one of the most accurately measured and permits a mass measurement of the tritium isotope.

(*d*) *More than two particles as end products.*—Here capture of the bombarding particle results in a disintegration where three or more end products are formed. An interesting example of this type of reaction is the emission of three α-particles as a result of deuteron bombardment of B^{10}:

$$_5B^{10} + {}_1D^2 \rightarrow 3\,{}_2He^4 + Q \qquad (13)$$

The "*Q*" of this reaction amounts to about 10 Mev and the energy is shared by the three α-particles with resulting ranges of about 4, 8, and 14 cms. The same reaction can be induced by proton bombardment of the more abundant $_5B^{11}$ isotope, but it yields about 1 Mev less energy.

7.09 Energetics of Nuclear Reactions

Suppose that a copper target is placed in a cyclotron beam and bombarded with deuterons. Several nuclear reactions might be expected from bombardment of the most abundant $_{29}Cu^{63}$ isotope.

Except for the (*d*, *d*) reaction which may be regarded as simple scattering, all of the above reactions are *bona fide* reactions which have been

$$
{}_{29}Cu^{63} + {}_{1}D^{2} \rightarrow
\begin{cases}
{}_{30}Zn^{64} + {}_{0}n^{1} & (d,n) \\
{}_{30}Zn^{63} + 2{}_{0}n^{1} & (d,2n) \\
{}_{29}Cu^{64} + {}_{1}H^{1} & (d,p) \\
{}_{29}Cu^{63} + {}_{1}D^{2} & (d,d) \\
{}_{29}Cu^{62} + {}_{1}H^{3} & (d,t) \\
{}_{28}Ni^{61} + {}_{2}He^{4} & (d,\alpha)
\end{cases}
\qquad (14)
$$

observed. Now the question arises: For a given bombardment, which of the reactions will occur?

The cyclotron can be adjusted so that it produces a fairly monoenergetic beam of deuterons of any energy. It is found, for example, that the d–$2n$ reaction is absent at low energies but becomes significant for 10 Mev deuterons. There is thus, what is called a *threshold energy* which must be reached before certain of the above reactions will go. It is possible to predict which of the above reactions will go; in other words, the threshold energy can be calculated from an evaluation of the energetics of the process.

Of the heavy disintegration products listed above, three exhibit artificial radioactivity and decay by $\beta-$ or $\beta+$ emission or by *K electron capture*. Both ${}_{30}Zn^{63}$ and ${}_{29}Cu^{62}$ are positron-emitters. The decay for ${}_{29}Cu^{62}$ is:

$$
{}_{29}Cu^{62} \xrightarrow{10.5\text{m}} {}_{28}Ni^{62} + {}_{+1}e^{0} + 2.6 \text{ Mev} \qquad (15)
$$

Here the figures 10.5 m. (minutes), written above the arrow, denote the half life for positron emission. The tritium produced in forming ${}_{29}Cu^{62}$ is also radioactive, so this reaction yields two artificially radioactive end products.

In addition, the disintegration product ${}_{29}Cu^{64}$ is artificially radioactive and is remarkable in that it may decay either by $\beta+$ emission, by $\beta-$ emission, or by *K electron capture*. Such an isotope is known as an *isomer*. Although the nuclear disintegrations which have been discussed for Eq. (14) are all instantaneous, it is also known that delayed radioactivity (artificial) is observed for the reaction:

$$
{}_{29}Cu^{63} + {}_{1}D^{2} \rightarrow {}_{30}Zn^{65} \qquad (16)
$$

This isotope also exhibits *isomerism*. About 40 pairs of nuclear isomers are known, i. e., isotopes of the same mass and charge but having different decay schemes. For example, ${}_{30}Zn^{65}$ may decay by any of the following schemes:

$$
{}_{30}Zn^{65} \rightarrow
\begin{cases}
{}_{29}Cu^{65} + {}_{+1}e^{0} & \text{(Positron emission)} \\
{}_{31}Ga^{65} + {}_{-1}e^{0} & (\beta\text{-decay}) \\
{}_{29}Cu^{65} - {}_{-1}e^{0} & \text{(K-electron capture)}
\end{cases}
$$

The significance of the negative sign in the last equation is that the electron is not emitted but is absorbed. The absorption or capture of a K shell electron into the nucleus produces the same product nucleus (example ${}_{29}Cu^{65}$) as would result if positron emission occurred.

It is clear that a bombarding particle can cause a variety of nuclear reactions to take place. The extent to which any one reaction occurs depends upon the energy of the bombarding particle.

7.10 Positron Emission and K-Electron Capture

In general if the number of neutrons in a disintegration product is too small in comparison to the number of protons, the nucleus will reduce its charge by one unit by positron emission. Positron emission occurs only if the energy difference between the original and product nucleus (due to difference in mass) is greater than $2m_0c^2$. Here m_0 is the rest mass of the electron so that the available energy in order to realize positron emission must be greater than 1 Mev. If the available energy is less than 1 Mev positron emission will not occur. Therefore in positron emission, the positron will always have 1 Mev less kinetic energy than if β-decay had occurred. In other words, if the available energy between parent and product nuclei is 3 Mev, then for positron emission, a positron with 2 Mev energy will be emitted.

If the disintegration would make available less than 1 Mev energy, the reaction can still go but it will take place in a different way. The parent nucleus will capture an electron from the K shell (K electron capture) and subsequently emit a quantum of energy $h\nu$ in order to rid itself of excess energy. The nucleus might pull into itself an L shell electron, but a K electron capture is much more probable. The general reaction is given by:

$$
Z^{A} + {}_{-1}e^{0} \rightarrow (Z-1)^{A} + h\nu \qquad (18)
$$

Since the process leaves a vacancy in the K shell, another orbital electron will drop down into the

K shell thus emitting a K X-ray quantum. Furthermore, if the nucleus is left in an excited state, it may emit a gamma ray from the nucleus. Thus K electron capture may involve the emission of two photons—one from the nucleus and one from the atom. It should be pointed out that the X-ray emitted will be characteristic of the product atom.

The absorption of positrons leads to annihilation of matter, in that the positron unites with an ordinary electron to produce gamma radiations. Thus the annihilation process is the inverse of pair production. Theoretically it is not possible for an annihilation to yield a single quantum of 1 Mev energy, if only an electron and positron are involved. In this case, two photons of 0.5 Mev energy are emitted, thus satisfying the laws of conservation of momentum and energy. If, however, the combination of an electron and positron takes place near the nuclear field, the massive nucleus can enter into the reaction by absorbing a small amount of energy. In such an event, a single photon of 1 Mev can be emitted. Both types of radiation, the 0.5 and the 1.0 Mev photons are observed experimentally. The reaction can be written as:

$$\beta^+ + e^- \rightarrow 2\gamma(0.5 \text{ Mev})$$
$$\text{or} \qquad \beta^+ + e^- \rightarrow \gamma(1.0 \text{ Mev}) \qquad (19)$$

7.11 Theory of Nuclear Reactions

The nature of the mechanism of nuclear reactions may be understood from a consideration of the following:

(*a*) The Bohr model of the nucleus.
(*b*) The concept of nuclear potential barriers.
(*c*) The application of the conservation laws.
(*d*) The application of wave mechanics.
(*e*) The concept of nuclear cross sections.

Bohr conceived of a nuclear reaction as a two-step process:

First, the incident particle and the target nucleus amalgamate to form an intermediate nucleus.

Second, this intermediate or compound nucleus disintegrates into the reaction products.

On a time scale, the first step takes only about 10^{-21} seconds, whereas the disintegration (this does not apply to the decay of artificial radioisotopes but only to other nuclear reactions) takes about 10^{-12} seconds. In the compound nucleus, the excess energy must be assumed to be temporarily shared by all nucleons. That this must be true is clear from the comparatively long life (10^{-12} seconds is long in nuclear time units) of the compound nucleus, for in 10^{-12} seconds all the nucleons make many collisions with each other and split up the excess energy among themselves. Furthermore, Bohr's conception of this process assumes that the disintegration of the compound nucleus is an event which is not directly connected with the original amalgamation process. The way in which the compound nucleus disintegrates depends upon a competition between the various reactions which are energetically possible. In fact, it is expected and observed that the specific reaction which requires the least energy will take place first. However, it is no exaggeration to state that practically any nuclear reaction can be realized if it is energetically possible. The reaction may go with extremely low yield or efficiency but it will go.

Compound nuclei are relatively stable in the sense that they hold together for a much longer time than it takes the neutron to traverse the nucleus. The latter time is equal to a nuclear diameter (10^{-12} cms.) divided by the neutron velocity (10^9 cm./sec.) which is about 10^{-21} seconds. Since the compound nucleus exists for about 10^{-14} secs., this is 10^7 times greater than the neutron traversal time. In general, the emission of a particle from the compound nucleus depends upon the probability that any one nucleon will receive sufficient energy to escape from the nucleus.

It will be shown that most neutron capture reactions have highest cross section at low velocities. This is understandable on the basis that slow neutrons spend more time in the vicinity of the nucleus and are thus more apt to be absorbed. In fact, for a neutron traveling with a velocity v, the probability for absorption is proportional to the time that the neutron remains in the vicinity of the nucleus; this is merely a time equal to $1/v$. This law, called the *1/v law*, applies to slow neutrons but it is sometimes also valid for higher energies. Neutrons are also often absorbed by *resonance capture*. In such cases, neutrons must have an energy which is the same

as that of certain energy levels of the nucleus. For example, the neutron capture cross section curve of uranium as a function of energy exhibits sharp peaks at low energies. These are called *resonance peaks*. Breit and Wigner have developed a theory of the resonance structure of nuclei on the basis of assuming a certain structure to the nuclear energy levels.

An interesting concept of nuclear reactions is involved in thinking of the compound nucleus as an aggregate of nucleons having an effective *nuclear temperature*. On the liquid drop model of the nucleus, all of the nucleons are in a constant state of collision and have an average kinetic energy which can be translated into a nuclear temperature by the equation:

$$\frac{1}{2}mv^2=\frac{3}{2}kT \qquad (20)$$

where k is the Boltzmann constant and T is the absolute temperature. The addition of a neutron to a nucleus by the capture process gives the compound nucleus the kinetic energy of the neutron plus the binding energy (8 Mev) of the neutron. This additional energy makes itself manifest in increased motion of the nucleons and raises the nuclear temperature. Bohr has estimated that the capture of a 10 Mev neutron by a heavy nucleus raises the temperature to about 10^{10} °C. At this high temperature the emission of a neutron can be thought of as a *boiling off* process. When a neutron is boiled off, it carries its binding energy as well as kinetic energy. Thereupon the result ing nucleus drops in temperature. This boiling-off analogy is valid for heavy nuclei and high excitation energies (>8 Mev) where the nuclear energy levels fall close together. For low excitation energies, the energy levels are far apart (100,000 e.v.) whereas for 8 Mev (the binding energy of one neutron) the level spacings are much closer, being separated by 10 to 100 e.v. At still higher energies (>10 Mev) the energy level spacings are only 1 e.v. or less apart, thus forming a continuum of levels.

7.12 The Production of Neutrons

The production of neutrons by the α-n reaction has already been discussed. Examples will be given of the d-n, p-n, and γ-n reactions.

(*a*) *The d-n reaction.*—The D on D reaction was discussed in section (7.08). This was an example of a d-p reaction. There is in addition, with the D on D reaction, a very important d-n reaction which goes:

$$_1D^2+{}_1D^2\rightarrow{}_2He^3+{}_0n^1+3.2\text{ Mev} \qquad (21)$$

Due to the mass difference of 0.0034 m.u. a Q of 3.2 Mev is imparted to the neutron and the rare isotope of helium. This reaction goes with deuterons of only 100 Kev and yields 1 neutron for every 10^6 deuterons. The D on D reaction is a relatively efficient one for producing neutrons. Cyclotrons running with a 10 microampere beam bombarding a target of heavy ice yield about 10^8 neutrons/second. This corresponds to a yield of about 1 neutron for 10^5 deuterons.

(*b*) *The p-n reaction.*—As an example of the production of neutrons by proton bombardment consider ${}_3Li^7$ as a target element. Then:

$$_3Li^7+{}_1H^1\rightarrow{}_4Be^7+{}_0n^1+Q \qquad (22)$$

Because of the fact that ${}_4Be^7$ has only 3 neutrons and 4 protons, it is to be expected that it will try to overcome this neutron deficit by positron emission. This actually is observed, and therefore 1 Mev of energy must be supplied by the proton for this effect. In addition, the neutron is heavier in mass than the proton by about 0.8 Mev so that the total Q of the above reaction is -1.8 Mev. The negative sign means that 1.8 Mev of energy has to be supplied by the proton for the reaction to start. This further means that for 1.8 Mev incident protons, the neutrons are produced with very little energy. Experimentally a threshold value of 1.86 Mev has been measured for this reaction, thus confirming the validity of the prediction. This reaction furnishes a very convenient means of producing mono-energetic neutrons of any energy, simply by varying the energy of the incident protons.

(*c*) *The γ-n reaction.*—Bombardment of deuterium and ${}_4Be^9$ with gamma rays, yields what is termed the photoelectric production of neutrons. While the process, in common with most gamma-ray bombardments, has a very low yield, it is important because it permits an accurate evaluation of the mass of the neutron. Consider the reaction with deuterium.

$$_1D^2+h\nu\rightarrow{}_1H^1+{}_0n^1+Q \qquad (23)$$

If γ rays of 2.62 Mev from ThC'' are used and if the proton ranges are accurately measured, the Q of the reaction will be:

$$2.62-2E_p=-Q \text{ and } E_p=0.45 \text{ Mev}$$

since the energy carried off by the neutron will be almost equal to that of the proton. This yields $Q=-2.2$ Mev and means that the neutron is bound to the deuteron with 2.2 Mev binding energy. Writing Eq. (23) in terms of the masses involved and using 1 m.u. as equal to 931 Mev, the mass of the neutron can be accurately obtained.

$$2.01473+\frac{2.62}{931}=1.00813+M_n+\frac{0.45}{931}$$

$$M_n=1.00893 \text{ m.u.}$$

7.13 Neutron Induced Reactions

Although the neutron is an uncharged particle, its energy can be expressed simply in electron volts. It is a matter of common practice to classify neutrons as thermal, slow, or fast according to the following schedule:

Neutron group	Energy in e.v.
Thermal	0.03 e.v.
Slow	1 e.v.–100 e.v.
Intermediate	100 e.v.–1 Mev.
Fast	Over 1 Mev.

Thermal neutrons are those which have an average energy of $\frac{1}{30}$ e.v., corresponding to the energy of a neutron in equilibrium with air at room temperature. Since these thermal neutrons are strongly absorbed by cadmium they are sometimes called "*C*" neutrons. Rhodium also strongly absorbs neutrons of slightly higher energy; other elements are listed in the following table in order of increasing neutron energy.

Neutron group	Absorbing element	Resonance energy (e.v.)
"C"	Cadmium	0. 2
"D"	Rhodium	1. 0
"I"	Indium	1. 4
"A"	Silver	5. 0

Even before discussing the specific neutron induced reactions, the above data indicate that neutrons exhibit unusual properties for reaction at extremely low energies. This remarkable property is due to the fact that neutrons, being uncharged, do not have to penetrate a potential barrier in order to enter the nucleus. Some elements, such as cadmium, exhibit truly enormous cross sections of several thousand barns for thermal neutron capture.

In general, neutrons induce a very large number of reactions. Only a few examples will be given for each of the following reactions (n, γ), (n, p) (n, α), (n, n) and $(n, 2_n)$. A discussion of the most unusual neutron induced reaction, namely fission, will be given in the next chapter.

(*a*) *The n-γ reaction or "neutron capture".*— When a neutron strikes a nucleus, it may enter it and be captured. This process increases the mass of the original nucleus by +1 and forms an isotope of it. The new isotope may be stable or it may be radioactive. If stable, it will show no gamma ray emission except for the instantaneous radiation produced in the capture process whereas the unstable isotope will decay. The gamma rays emitted in the capture process are called capture gammas. Since the n to p ratio in the product nucleus increases as a result of neutron capture, the radioactive products decay by β-emission. Example of simple non-radioactive capture:

$$_{48}Cd^{113}+{}_0n^1 \longrightarrow {}_{48}Cd^{114}+h\nu \qquad (24)$$

It is known that $_{48}Cd^{114}$ is stable. There are three remarkable features of the neutron capture by cadmium. First, cadmium has a cross section of about 4,000 barns; thus it virtually soaks up slow neutrons. In fact, in the neutron reactions to be described in the next chapter, rods are plated with a coat of cadmium to allow for control of the reactor. Recent experiments show a second remarkable feature of the reaction. Figure 7–6 shows a mass spectrum of cadmium which has been irradiated very strongly with thermal neutrons. It is easily seen that the Cd^{113} isotope is depleted and Cd^{114} is enhanced in abundance, thus proving that Cd^{113} is the only isotope of six cadmium isotopes to absorb the neutrons strongly. Finally, Cd^{113} shows this enormous capture cross section only for neutrons of thermal (1/30 ev) energy. At other higher energies it is a relatively poor absorber.

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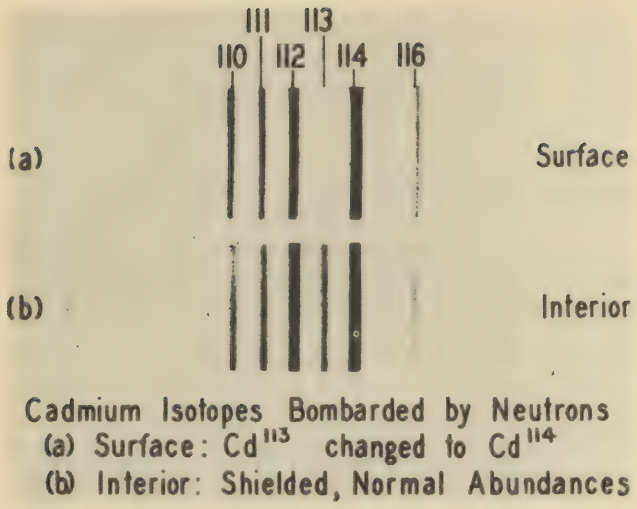

FIGURE 7–6.—Mass spectrum of irradiated cadmium.
Photograph by Prof. A. J. Dempster

Example of radiative capture:

$$_{45}Rh^{103}+{}_0n^1 \longrightarrow {}_{45}Rh^{104}+\gamma \qquad (25)$$

$$_{45}Rh^{104} \xrightarrow{4^m 8} {}_{46}Pd^{104}+{}_{-1}e^0+2.3 \text{ Mev.}$$

This is a very common reaction which has been observed in many other cases, totaling over 100 reactions. The cross section of rhodium for neutron capture may be obtained from a measurement of the captured gamma rays or by observing the intensity of the β-decay of Rh^{104}.

All elements except helium are known to capture thermal neutrons. Since the emission of a charged particle after capture involves additional energy, a competition usually exists between neutron reemission (scattering) and γ-ray emission (radiative neutron capture). In general, the probability that capture will occur follows a $1/v$ law, that is, the cross section varies as the reciprocal of the neutron velocity. Boron, for example, follows this law even to quite high neutron energies. On the other hand, cadmium, gadolinium, and dysprosium have thermal absorption cross sections which do not follow the $1/v$ law. The reason for this is that these isotopes have excited states such that when capture occurs at certain energies corresponding to these states, resonance absorption takes place. Resonance absorption takes place in the thermal region for a few isotopes and others exhibit resonance for slow neutrons, usually below 100 e.v. energy. This phenomenon may take place at still higher energies, but in general the cross sections become larger as the neutron energies are progressively lowered. The cross section for neutron capture in cadmium is plotted in figure 7–7

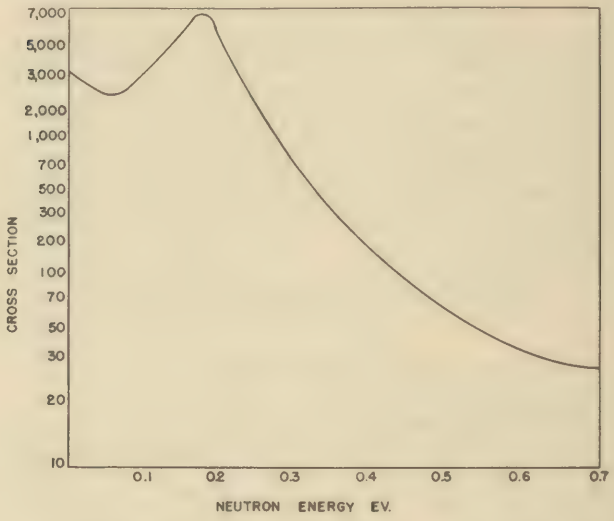

FIGURE 7–7.—Cross section for neutron capture by cadmium as a function of energy.

(*b*) *The n-p reaction.*—While the neutron can slip into a nucleus without being affected by the potential barrier, the *n-p* reaction still involves a consideration of the potential barrier, because a charged particle, the proton, has to escape through it. Thus one might expect that neutrons of higher energy will produce greater yields in the *n-p* reaction, since the proton will have a better chance to leak through or surmount the barrier. As an example, consider the absorption of a neutron into an Al^{27} nucleus:

$$_{13}Al^{27}+{}_0n^1 \rightarrow {}_{12}Mg^{27}+{}_1H^1+Q \qquad (26)$$

In effect, the mass of the original nucleus remains unchanged. All that has happened is that $_{13}Al^{27}$ has exchanged a proton (emitted) for a neutron (absorbed).

The masses on the left hand side of the equation	=27. 0988
The masses on the right hand side of the equation	=27. 1009
	−0. 0021 m.u.

Therefore the neutron has to supply (0.0021) (931)

Mev=2 Mev to the nucleus before the reaction will go. This means that the *n-p* reaction is a fast neutron reaction. Measurement of the cross section for the *n-p* reaction in Al^{27} gives a curve as shown in figure 7–8.

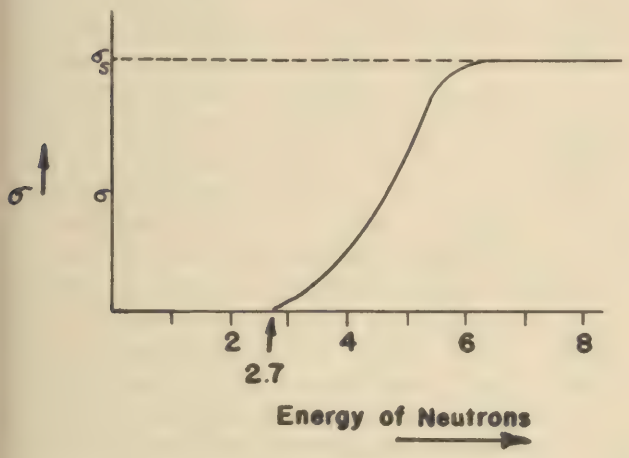

FIGURE 7–8.—Cross section as a function of energy for *n-p* reaction in Al^{27}.

The threshold energy comes at 2.7 Mev instead of the 2 Mev as predicted by consideration of the energetics of the reaction. What has been neglected in the prediction is that no account has been taken of the energy for the proton to escape the potential barrier. When this is included in the calculation the threshold energy is compatible with our analysis. As the energy of the incident neutrons increases, the protons find it increasingly easier to escape from the nucleus until the neutrons reach a saturation cross section (σ_s) at an energy of 5.9 Mev. After that, the potential barrier does not interfere with proton escape from the nucleus. It should be clear from figure 7–8 that such cross section curves tell a great deal about the structure of the potential barrier. Since many of the product nuclei formed by the *n-p* reaction are β-emitters, subsequent β-decay causes the product nucleus to revert to the original form that it had before the transmutation. Over 50 *n-p* reactions are now known, but most of these reactions are confined to elements with $Z<40$, for the heavier elements present too high a potential barrier for proton emission.

(*c*) *The n-α reaction.*—This reaction is of very practical value when applied to boron, for it makes possible an easy means of detecting neutrons. Consider the neutron induced reaction in $_5B^{10}$ (the less abundant of the two boron isotopes):

$$_5B^{10}+{}_0n^1\rightarrow{}_3Li^7+{}_2He^4+Q \qquad (27)$$

This reaction has a thermal cross section of 3,800 barns for the B^{10} isotope and theoretically releases 3 Mev of energy. However, Li^7 is often left in an excited state which reduces the kinetic energy imparted to the α-particle. A 2.5 Mev α-particle is extremely useful, especially when it is produced by such an efficient absorption process, for it means that the alpha can be counted and serve as a measure of the neutron flux. This is accomplished in an ionization chamber or counter filled with BF_3, boron trifluoride, or lined with a boron compound. The separation of $_5B^{10}$ from the more abundant but poorer absorber $_5B^{11}$ allows these devices to be made even more efficient. Boron which is depleted in $_5B^{11}$ and thus enhanced in $_5B^{10}$ is known as enriched boron. Some 40 *n-α* reactions are known, and as was the case for the *n-p* reaction, these are limited to elements with $Z<40$.

(*d*) *The n-n reaction (or inelastic neutron scattering).*—In such reactions, there is usually no change in the target nucleus except perhaps for the excitation of the nucleus to a higher energy state with the subsequent emission of a photon. The reaction for any element of mass number Z is given by:

$$Z^A+{}_0n^1\rightarrow Z^A+{}_0n^1+Q \qquad (28)$$

where it is understood that the product nucleus Z^A is in an excited state. Experimentally it is observed that the Q for the reaction is negative, indicating that the incident neutron has more energy than the ejected neutron. For the incident neutron to lose kinetic energy in the collision, it must form an intermediate nucleus with the bombarded nucleus. Cross sections for this *n-n* or more properly *n-n*+γ reaction are about equal to the physical cross sectional area of the nucleus, and this fact provides a measure of the nuclear radius. Only a few reactions of this type are known which result in a radioactive product.

Strictly speaking, a pure *n-n* reaction would be merely elastic neutron scattering with no energy being lost by the incident neutron. Elastic neutron scattering is thought of as a process in which the incident neutron shoots through the

nucleus too quickly to undergo interaction with the nucleus and suffer energy loss. As such, this type of scattering leaves the nucleus unexcited. Because elastic collisions are so important in understanding how neutrons are slowed down, the subject will be treated more extensively in section 7.14.

(*e*) *The n-2n reaction.*—To remove a neutron from a nucleus requires that energy equal to that of the binding energy for the neutron be supplied to the nucleus. Earlier it was noted that the binding energy for a single neutron averages about 8 or 9 Mev. Therefore, if a very fast (say, 10 Mev) neutron were to collide with a nucleus, it might be expected that two neutrons would be ejected. Furthermore, for the lighter elements, the loss of a neutron would lower the N/P ratio and make positron emission the probable decay scheme for the product nucleus. As before, this would mean an additional 1 Mev would be required, making the total energy to be supplied by the neutron about 10 Mev.

Such reactions are commonly observed when neutrons from a cyclotron bombardment of deuterons on lithium are used. A typical reaction, that for potassium, is illustrated by:

$$_{19}K^{39}+{}_0n^1\rightarrow{}_{19}K^{38}+{}_0n^1+{}_0n^1+Q \qquad (29)$$

As expected, K^{38} is a positron emitter, decaying with a half life of 7.7 min. by emitting a positron of 2.3 Mev.

Over 100 *n–2n* reactions have been observed, most of which result in product nuclei which are β-emitters. It is understandable that this decay scheme is feasible, since for larger numbers of nucleons in a nucleus, the depletion of the neutrons by one does not so seriously upset the delicate balance as it does in lighter nuclei.

Using the same line of reasoning that the detachment of 1 neutron requires 10 Mev, it might be indicated that three neutrons could be ejected by using 20 Mev neutrons. A few reactions of this type have been observed but it is found that a *n–2n+p* reaction also occurs in addition to the *n–3n* reaction.

7.14 Energy Release From Nuclear Reactions.

In the foregoing sections, thermal neutrons have been indicated as being important in many neutron-induced reactions. However no mention was made of the mechanism by which neutrons acquired thermal velocities. Actually thermal neutrons are produced by slowing down fast neutrons through elastic collisions with atoms. It is rather paradoxical that after it has frittered away all but a fraction of an electron volt of energy, the neutron should be so effective in inducing nuclear reactions.

Of the reactions which have been discussed in this chapter, none have appeared to produce high yields so that they could be used for any practical application nor were any mechanisms apparent which would allow an exoergic reaction to perpetuate itself. However for certain reactions in the light elements, say, the p–2α reaction in lithium it is apparent that per nuclear disintegration enormous energy is liberated. Starting with 8.02631 gms., the reaction yields products of 8.00778 gms, thereby losing 0.01853 for a gram atom. Thus the complete conversion of 7 gms. of $_3Li^7$ would yield a total of 400,000 kwhr. of energy. Per atom, the reaction would release 17.3 Mev energy. It is a far cry from disintegrating a single $_3Li^7$ atom to completely converting 7 gms. of $_3Li^7$ by proton bombardment. Only 1 in about 10^5 protons results in a disintegration and if the α-particles produced by the reaction were energetic enough to cause an α–p reaction the yield would be very small. There would thus be no possibility of this reaction perpetuating itself. However, per nucleon in the $_3Li^7$ atom, about 2½ Mev of energy is released. This is a very sizeable amount of energy per nucleon as contrasted with 200 Mev released in the fission of uranium. The latter released only $\frac{200}{235}$ or less than 1 Mev per nucleon but it has the enormous advantage of being a self perpetuating reaction.

7.15 Cosmic Radiation

All of the reactions discussed so far have involved radiation of less than 20 Mev. In cosmic radiation, however, energies of a quite different order of magnitude are present.

The words *the cosmic ray* are so frequently used that the layman believes that there is only one type of cosmic ray and he is disappointed when no simple description of this ray can be given. Actually there are several different kinds of cosmic rays. However, two general types of cosmic rays may be defined.

Primaries.—This category includes protons which come from some cosmic origin beyond our own galaxy. There may also be a small percentage of electromagnetic radiation or high energy electrons. Due to the effect of the earth's magnetic field only the highest energy ($>10^9$ e. v.) protons are able to enter the atmosphere at the equator. On the other hand protons of all energies are allowed to come in at the poles. When they strike the top of the earth's atmosphere, the protons interact with the nitrogen nuclei to form secondary particles.

Secondaries.—The primary particles produce new sub-nuclear particles called mesons or mesotrons. Mesotrons are particles which have a mass about 200 times that of the electron and may carry a single positive or a single negative charge. Created high in the atmosphere, the mesotrons travel down toward the earth with high velocity and great penetrating power. As a particle, the mesotron is most unusual for it is unstable and decays in about 2 microseconds to form an electron and a neutrino. In addition high energy secondary electrons and photons are found in the cosmic radiation. Due to the fact that these particles have enormous energies from 10^7 to 10^{15} e. v. they interact strongly with matter and produce other tertiary cosmic rays such as neutrons and alpha particles.

The cosmic ray intensity shows considerable variation with altitude and geomagnetic latitude. Examples of this are given in figure 7–9. It will be noted that the primaries produce great numbers of secondaries as is evident from the maximum in the curves. Even at high altitudes the cosmic radiation intensity is only about 1 milliroentgen/day.

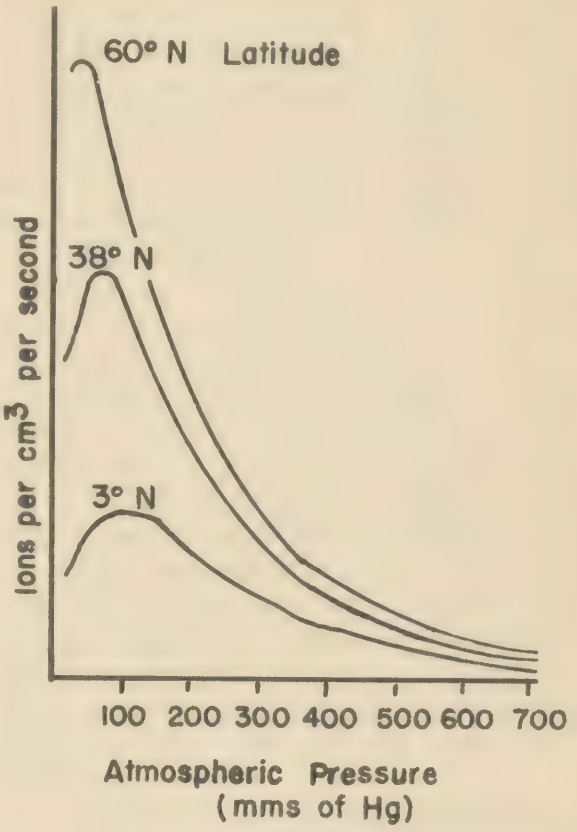

FIGURE 7–9.—Total cosmic ray intensity as a function of altitude.

Chapter 8

NEUTRON PHYSICS AND FISSION

8.01 The Discovery of Nuclear Fission

Soon after Chadwick had announced the discovery of the neutron, Enrico Fermi and his collaborators in Italy began bombarding uranium with these new particles. Upon irradiating uranium with neutrons from a Ra-Be source, they found that several activities were induced in the element, and they were puzzled by the fact that these activities did not correspond to those which might be expected, i. e. elements with atomic numbers 86–92. It was then believed (and this is now known to have been fallacious) that these induced activities were due to elements of atomic number higher than 92. Such elements are called *transuranium* elements. Fermi's work stimulated research in other countries, and in 1938 Curie and Savitch performed chemical separations on neutron-irradiated uranium and discovered that an element with a 3.5 hour half life was precipitated out with lanthanum. The investigators attributed the 3.5 hour activity to a transuranium element because lanthanum was not known to have a radioactivity of that half life.

In the same year, Hahn and Strassman, repeating the Curie-Savitch experiment, proved that the 3.5 hour activity was due to barium, whose disintegration product was lanthanum. They thus proved that the neutron induces in uranium a reaction which causes the nucleus to split up into two heavy fragments. This splitting up process they termed *fission*. Curie and Savitch had indeed observed the phenomenon of fission, but they did not recognize it as such.

The discovery of fission stimulated great activity in the United States. This activity, begun in 1939 with the investigation of fission phenomena in almost every nuclear physics laboratory, continued at an ever increasing pace and culminated in the large scale release of nuclear energy. Prior to the war the private researches of laboratories all over the world had revealed many new facts about these phenomena. A brief summary of the prewar status of nuclear fission is given in the next section.

By the process of the splitting up of uranium, two smaller fragments are produced which together weigh considerably less than the original mass of the uranium nucleus. This disparity in mass is a real one and means that the considerable quantity of energy, roughly 200 Mev, is liberated in the fission process. It was therefore of the greatest interest to understand, on a theoretical basis, what heavy isotopes were capable of being fissioned (called *fissionable materials*) and why these isotopes fissioned.

Meitner and Frisch pointed out the analogy between the fission process and the division of a small liquid sphere into smaller drops as a result of a physical deformation of the drop. They noted that the mutual repulsion of protons in very heavy nuclei is able to predominate to a great extent over the forces holding the nucleus together. Thus a small amount of energy added to a uranium nucleus may produce such a deformation that the short range nuclear forces are no longer able to compete with the longer range repulsive forces and the nucleus tears itself into two parts. Each of these *fission fragments* then carries off very high kinetic energy, the exact value of which depends on its specific mass.

In 1939, Bohr and Wheeler published their paper "The Mechanism of Nuclear Fission" in which they discuss the theoretical basis for fission. Their calculations predicted that the fission of uranium under the slow neutron bombardment was due to the U^{235} isotope rather than that of the more abundant U^{238} isotope. Less than a year later, a group of investigators separated a very small quantity of U^{235} from U^{238} and proved that it was responsible for the fission. It was recognized at the time that the fission process gave rise to extra neutrons which might be used for further producing more fissions in a *chain reaction*.

Five years after it was shown that U^{235} fissioned under thermal neutron bombardment, an atomic bomb was successfully detonated in New Mexico. The term *atomic bomb* is a misnomer which persists through popular usage; actually it should be called a *nuclear* bomb, since it depends upon the release of nuclear energy.

8.02 Fission Phenomena

In June of 1940, many fundamental aspects of nuclear fission had been investigated and published in the scientific periodicals. It is of interest to summarize the state of knowledge in this new expanding field as was done by H. D. Smyth in his report "Atomic Energy for Military Purposes."[1]

All of the following information was generally known in June 1940, both here and abroad:

(*a*) That three elements—uranium, thorium, and protactinium—when bombarded by neutrons sometimes split into approximately equal fragments, and that these fragments were isotopes of elements in the middle of the periodic table, ranging from selenium (Z=34) to lanthanum (Z=57).

(*b*) That most of these fission fragments were unstable, decaying radioactively by successive emission of β-particles through a series of elements to various stable forms.

(*c*) That these fission fragments had very great kinetic energy.

(*d*) That fission of thorium and protoactinium was caused only by fast neutrons (velocities of the order of thousands of miles per second).

(*e*) That fission of uranium could be produced by fast or slow (so-called thermal velocity) neutrons; specifically, that thermal neutrons caused fission in one isotope, U–235, but not in the other, U–238, and that fast neutrons had a lower probability of causing fission in U–235 than thermal neutrons.

(*f*) That at certain neutron speeds there was a large capture cross section in U–238 producing U–239 but not fission.

(*g*) That the energy released per fission of a uranium nucleus was approximately 200 million electron volts.

(*h*) That high-speed neutrons were emitted in the process of fission.

(*i*) That the average number of neutrons released per fission was somewhere between one and three.

(*j*) That high-speed neutrons could lose energy by inelastic collison with uranium nuclei without any nuclear reaction taking place.

(*k*) That most of this information was consistent with the semi-empirical theory of nuclear structure worked out by Bohr and Wheeler and others; this suggested that predictions based on this theory had a fair chance of success.

Looking back on the year 1940, we see that all the prerequisites to a serious attack on the problem of producing atomic bombs and controlling atomic power were at hand. It had been proved that mass and energy were equivalent. It had been proved that the neutrons initiating fission of uranium reproduced themselves in the process and that therefore a multiplying chain reaction might occur with explosive force. To be sure, no one knew whether the required conditions could be achieved, but many scientists had clear ideas as to the problems involved and the directions in which solutions might be sought.

[1] The official report on the Development of the Atomic Bomb under the Auspices of the United States Government, 1940-45. By Henry De Wolf Smyth, chairman, Department of Physics, Princeton University, Consultant, Manhattan District, U. S. Corps of Engineers.

8.03 The Energy Released in Fission

Elements with atomic mass number less than 100 are energetically stable, and only the heavier elements are energetically disposed to the fission process. The following table of typical values for energy available, from a given parent nucleus and corresponding product nuclei illustrates how fission energy increases with increasing atomic number:

TABLE I

Parent nuclei	Product nuclei	Available fission energy
		Mev
$_{28}Ni^{61}$	$_{14}Si^{30}+{}_{14}Si^{31}$	−11
$_{50}Sn^{117}$	$_{25}Mn^{58}+{}_{25}Mn^{59}$	+10
$_{68}Er^{167}$	$_{34}Se^{83}+{}_{34}Se^{84}$	+94
$_{82}Pb^{206}$	$_{41}Nb^{103}+{}_{41}Nb^{103}$	+120
$_{92}U^{239}$	$_{46}Pd^{119}+{}_{46}Pd^{120}$	+200

In this and the following sections, the parent nucleus for fission will always be taken as the compound nucleus which includes the mass of the neutron producing fission. Thus in speaking of the fission of $_{92}U^{235}$, the compound nucleus $_{92}U^{236}$ will be used when considering mass relations of the product nuclei. Only a few heavy isotopes, all with an atomic weight greater than 220, are known to undergo fission. If one wishes to understand why fission occurs only for these heavy isotopes, it is clear that one must be able to present a qualitative or perhaps a semiquantitive picture of the fission mechanism. This picture must include everything which is known about the interaction of nucleons within the nucleus. One of the most revealing things which is known about the nucleus is the measure of its mass defect, for this immediately yields a value for the average binding energy per nucleon. Figure 8–1 shows a smoothed curve for the average binding energy per nucleon as a function of the atomic weight. The total binding energy per nucleus is equal to the product of the binding energy per nucleon and the number of nucleons.

A possible fission reaction is:

$$_{92}U^{235}+{}_{0}n^{1}\rightarrow({}_{92}U^{236})\rightarrow{}_{46}Pd^{118}+{}_{46}Pd^{118}+Q \quad (1)$$

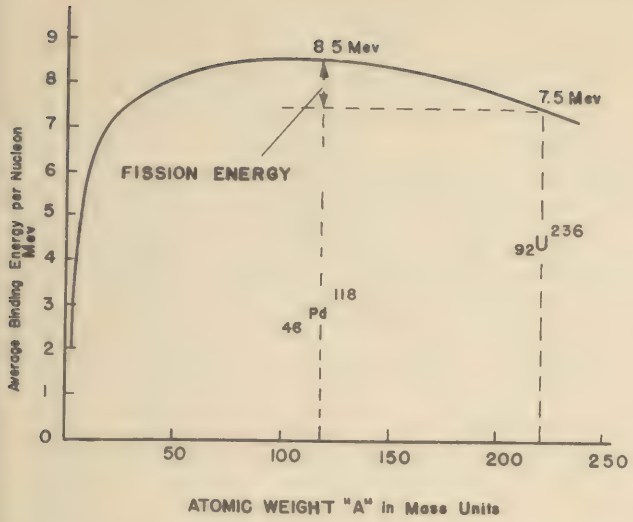

FIGURE 8–1.—Average binding energy per nucleon.

This equation is balanced with respect to both charge and mass. The energy released is equal to the binding energy of the product minus the binding energy of the parent. Thus for Eq. (1)

$$E_f = 118B_{118} + 118B_{118} - 236B_{236} \qquad (2)$$

where B is the binding energy per nucleon for the nucleus indicated by the subscript. From figure 8–1 the binding energy per nucleon for the palladium nucleus is 8.5 Mev and for $_{92}U^{236}$ it is 7.5 Mev. Thus

$$E_f = 236(8.5 - 7.5) = 236 \text{ Mev.} \qquad (3)$$

Considering the errors in the values for B, this is in fair agreement with what is actually measured for the fission energy.

8.04 The Binding Energy Equation

In the foregoing section, the use of binding energies allowed a very direct calculation of the total energy released in fission. The next section will show that if certain critical amounts of energy (excitation energies) are added to a uranium nucleus, it will undergo fission. The addition of such energy can come about as the binding of an additional neutron to the U^{235} nucleus. However, the nuclei will be shown to have different excitation energies, and it is therefore of the greatest importance to calculate the amount of energy with which a neutron binds itself to a nucleus. To do this, an equation may be derived semi-empirically so that the mass of any nucleus may be calculated from it:

$$M = \underset{a}{m_n(A-Z)} + \underset{b}{m_p Z} - \underset{c}{a_1 A} + \underset{d}{a_2 A^{2/3}} + \underset{e}{a_3 \frac{Z^2}{A^{1/3}}} + \underset{f}{a_4 \frac{\left(Z - \frac{A}{2}\right)^2}{A}} \pm \underset{g}{\delta} \qquad (4)$$

Term a b c d e f g

Where M is the exact mass of an isotope of charge Z and mass number A which would result from building up the nucleus from Z protons and $A-Z$ neutrons, taking into account the observed decreases in mass of the proton and neutron due to binding. This rather formidable equation, consisting of 7 terms each of which is a function of A and/or Z, will not be derived here. The significance of each term is as follows:

Term $a = [m_n(A-Z)]$ is simply the product of the mass of the free neutron (m_n) and the total number of neutrons in the nucleus.

Term $b = [m_p Z]$ is similarly the product of the mass of the free proton (m_p) and the total number of protons in the nucleus.

Terms c through g all make up the binding energy which is released when the free neutrons and protons are brought together to form the nucleus under consideration. This is equivalent to expressing analytically the empirical fact that nuclei have uniform density. This means that the volume occupied by a nucleus is proportional to the number of nucleons and consequently the radius is proportional to $A^{1/3}$.

Term c: The term ($a_1 A$) expresses the fact that the nucelons are held together by the attractive nuclear force, and therefore work was done and energy lost when the particles were fused. The constant of proportionality a_1 is numerically $+0.00504$.

Term d: ($a_2 A^{2/3}$) is a term which takes into account the fact that the surface of the nucleus contains nucleons which are not subject to the same interaction with other nucleons as are those in the interior. Surface nucleons are less tightly bound. It is for this reason that light nuclei have binding energies per nucleon less than those for medium heavy nuclei, since light nuclei have relatively greater surface area per unit volume.

Since the nuclear surface area is proportional to r^2 and since r is proportional to $A^{1/3}$, this effect will be proportional to $A^{2/3}$. Empirically, a_2 is a constant $= +0.014$.

Term e: $\left(a_3 \frac{Z^2}{A^{1/3}}\right)$ expresses the repulsive effect of the protons within the nucleus. For $A > 120$, this coulomb repulsion of the protons increases sufficiently to offset the attractive forces. It can be shown to be equal to $\frac{3e^2Z^2}{r}$.

The constant $a_3 = 0.000627$.

Term f: $\left[a_4 \frac{\left(Z - \frac{A}{2}\right)^2}{A}\right]$ takes account of the empirical fact that the number of protons in any nucleus tends to be equal to one half the total number of nucleons. This tendency may not seem apparent in heavy nuclei, where the number of neutrons is greater than the number of protons, but the two would be equal were it not for the electrostatic repulsion of the protons. Inside the nucleus there are neutron-proton, neutron-neutron, and proton-proton interactions. These interactions are of the same order of magnitude and account for the fact that nuclei tend to contain the same number of protons and neutrons. a_4, the constant of proportionality, is equal to 0.083.

Term g: Delta (δ) is a correction term which adjusts for small changes in energy due to the pairing of nucleons in the nucleus. This term may be:

$\delta = +k$ if A is even but Z is odd

$\delta = 0$ if A is odd

$\delta = -k$ if A is even and Z is even

and $k = \frac{0.036}{A^{3/4}}$

It thus takes into account the fact that nuclei with odd numbers and even numbers for Z and A are more or less stable according to table II.

Abundance of stable isotopes according to oddness—evenness of Z and A–Z.

It should be understood that the relative abundance of naturally occurring isotopes is a measure of their stability. For example ${}_8O^{16}$, an even-even isotope, is very abundant whereas ${}_8O^{17}$, an even-odd isotope is less common. Furthermore only four odd-odd isotopes occur in nature.

By simplifying Eq. (4) and substituting the constants a_1 a_2, a_3, a_4, the following equation is obtained:

$$M = 0.99389A - 0.0081Z + 0.014A^{2/3} + 0.00627\frac{Z^2}{A^{1/3}} + 0.083\left(Z - \frac{A}{2}\right)^2 + \delta \qquad (5)$$

TABLE II

A–Z \ Z	Even	Odd
Even	Most abundant	Moderately abundant.
Odd	Moderately abundant.	Least abundant.

It will be noted that this is a semiempirical equation into which has been put the contribution of all factors which are empirically known to effect binding energy. As such it is an approximate equation and gives a fairly reliable evaluation of nuclear masses for all but low values of A.

Suppose now that the binding energy of a neutron to a U^{235} nucleus be calculated:

Mass of U^{235} from Eq. 5	→235.11240 m.u.
Mass of the added neutron	→ 1.00893
Mass of $(U^{235}+n)$	→236.12133
Mass of U^{236} from Eq. 5	→236.11401
Difference in mass	→ .00732 m.u = 6.81 Mev

Similarly, the binding energy of a neutron to U^{238} can be found to be 5.31 Mev. The factor in Eq. 5 which yields a difference of 1.5 Mev in the binding energies for a neutron to U^{235} and U^{238} is the delta-term. In the next section, it will be seen that this difference of 1.5 Mev is sufficient to explain why U^{235} fissions with thermal neutrons but U^{238} does not.

8.05 The Theory of Fission—Energetics

From the results of the last section, the energy which will be given up to a compound nucleus by a captured neutron is now determined. It remains to be shown why this energy causes a fission reaction in certain heavy nuclei. Only a few isotopes undergo fission with thermal neutrons because there exists a threshold energy which must be supplied to the nucleus before fission will

occur. This threshold energy may be termed the *activation energy*. Perhaps this is best visualized as being the difference between E_c and E_f where E_c is the coulomb repulsive energy and E_f is the energy for symmetric fission; i. e., fission products of equal mass. Curves for E_c and E_f are plotted in Figure 8–2 as a function of the mass number. In this figure $E_c - E_f$ for $A=235$ is about 6 Mev. This means that a 6 Mev potential barrier exists for the two fission fragments which are trying to

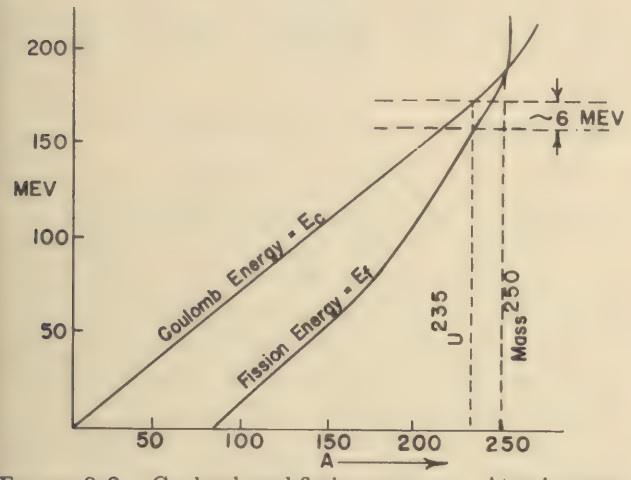

FIGURE 8–2.—Coulomb and fission energy vs. Atomic mass number.

escape. Once the fission energy curve crosses the coulomb energy curve, which it does at $A=250$, no stable isotope should exist.

Suppose that the energy of the two fission fragments (or of the compound nucleus) be considered as a function of the distance separating the two fragments. When the fragments are still in the nucleus ($r=2R$ where R is the fragment radius) the energy in the compound nucleus must be 200 Mev. When the fragments are very far apart ($r=\infty$) the energy must be zero. In between these two extremes only the coulomb forces will act and the curve can be represented as in figure 8–3. At distances equal to the fragment diameter ($r=2R$), the coulomb force no longer is effective and is indicated as abruptly ending at a finite value. It is the finite value which is important in considering fission, for the difference between it and the fission energy is the height of the potential barrier for fission. Accordingly, the problem of determining whether fission will occur can be divided into three categories. These are illustrated

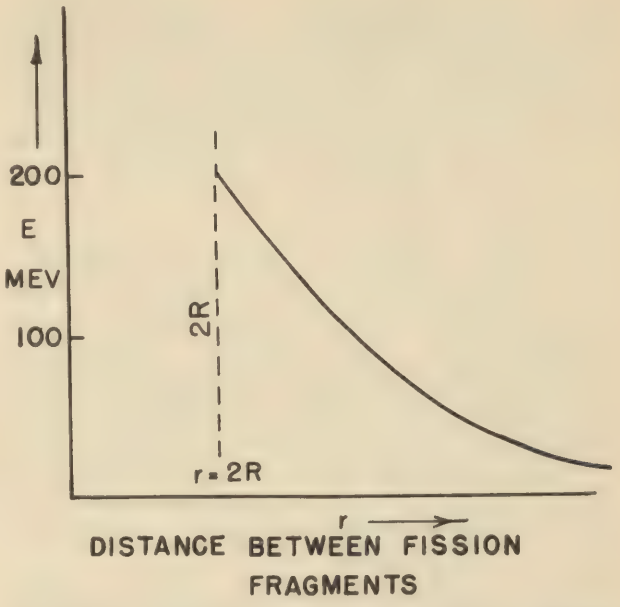

FIGURE 8–3.—Energy of a nucleus as a function of distance between two fission fragments.

in figure 8–4 where the curve given in figure 8–3 is presented again with three curves extending from $r=0$ to $r=2R$.

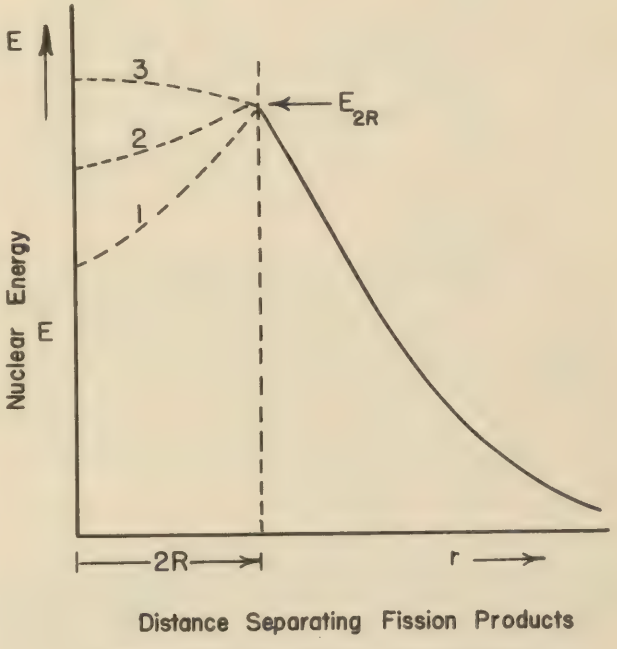

FIGURE 8–4.—Potential barrier for fission.

Let the coulomb energy at $r=2R$ be equal to E_{2R}. Then three cases are important

Case 1: $E_{2R} \ll E_f$ or $E_{2R} - E_f$ is negative. Such nuclei would be spontaneously unstable and would not exist in nature.

Case 2: $E_{2R} > E_f$ or $E_{2R} - E_f \approx 6$ Mev. Nuclei such as uranium, thorium, and transuranium elements (plutonium) fall in this category. The fission barrier for these materials is about 6 Mev.

Case 3: $E_{2R} \gg E_f$ or $E_{2R} - E_f > 50$ Mev. Light nuclei with $A < 100$ come in this category and are very stable with regard to fission.

The nuclei considered under Case 2 are of greatest interest, for the excitation energy is of the same magnitude as can be supplied by neutron absorption or by bombardment with light charged particles. Of the various means of inducing fission, the neutron absorption process is of most importance to this discussion.

Bohr and Wheeler calculated that the excitation energy for fission of U^{235} was 5.2 Mev and for U^{238} was 5.9 Mev. A slow neutron will add only 5.3 Mev to U^{238} and no fission will occur, but it will add 6.8 Mev to U^{235} and fission should occur. Thus, the bombardment of U^{235} with thermal neutrons suffices to excite the compound nucleus to a level greater than the excitation energy, thus overcoming the potential barrier and causing fission. If more energetic neutrons, say 2 Mev neutrons, are used to bombard U^{238}, the added kinetic energy will suffice to cause fission. This fast fission reaction in U^{238} cannot be used in the atomic bomb because other processes (see sec. 8.11) are more probable.

One might imagine that there might be a small probability for fission fragments to leak through the fission barrier analogous to alpha emission. This actually happens in the U^{238} nucleus but the half-life for the process is exceedingly long, about 10^{17} years. This phenomenon is called spontaneous fission and produces about 20 fissions per hour in a gram of uranium.

8.06 The Theory of Fission—Mechanics

It is not enough that the excitation energy for fission be exceeded in a nucleus because of the competition of nuclear processes. Thus, merely adding a certain quantity of energy to a nucleus does not insure that fission will occur, for other processes, such as the emission of light particles, might be more probable. If, however, the excitation energy is concentrated in the proper modes of oscillation of the nucleus, then fission will occur. The mechanics of the fission process (fig. 8–5) is pictured as consisting of a deformation of the otherwise spherical nucleus A into a nonspherical nucleus B. This nucleus deforms further producing a constriction in the middle C. Then the constriction narrows D producing a highly deformed product. Finally the constriction snaps, yielding two separate fission fragments or products E.

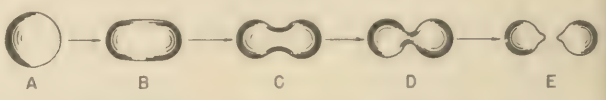

FIGURE 8–5.—Mechanics of fission process.

The fission process does not often yield fission products of equal mass and because of this, it is said to be asymmetric. Just why this asymmetry exists in not well understood. When the fission fragments appear, neutrons, β-particles, gamma quanta, and sometimes high energy α-particles are emitted. Furthermore, the fission products are themselves radioactive and emit β-particles as well as γ-rays. All of these radiations carry away some fraction of the total fission energy. The division of energy among the various products can be made between two equations:

$$\begin{array}{lcccccc} \text{Fissioned Nucleus} & \rightarrow & \text{Fission Fragments} & + \text{Neutrons} & + & \text{Gamma rays} & (6) \\ 200 \text{ Mev} & & 160 \text{ Mev Kinetic} & 15 \text{ Mev} & & 5 \text{ Mev} & \end{array}$$

$$\text{Radioactive decay of Fission fragments} \rightarrow \underbrace{\beta\text{-particles} + \gamma\text{-rays}}_{(+20 \text{ Mev})} \qquad (7)$$

This energy balance is only approximate, but it serves to illustrate where the total fission energy goes in the reaction.

Two types of neutrons produced by the fission process can be distinguished. *Prompt neutrons* are emitted instantaneously while *delayed neutrons* are emitted over a period of seconds after fission has occurred. The prompt neutrons comprise over 99 percent of all the neutrons emitted and apparently have their origin in the fission products. One might expect the prompt neutrons to be emitted by the compound nucleus, but it would appear that they are emitted from highly excited fission fragments within 10^{-12} seconds after fission.

The number of neutrons produced per fission averages between one and three. As they are emitted from the fission fragment, these neutrons have very high energy. As might be expected, where highly excited nuclei are involved, the fission gamma radiation is extremely penetrating.

8.07 Types of Fission and Cross Sections

Fission of U^{235} by thermal neutrons has already been discussed, and fast neutron fission of the same isotope has also been mentioned. In general the cross section for fission of U^{235} varies with the energy of the incident neutron. This cross section approximates a $1/v$ law. Other isotopes which are fissionable by neutrons are discussed in sections 8.11 and 8.14. For the present, only the fission of uranium will be discussed.

Protons and deuterons may also be used to induce fission in uranium. These processes are written as (p, f) and (d, f) reactions. In general, cross sections for these reactions are rather low. Another type of fission process, called photofission, is known. In this reaction, the fission is induced by the nucleus absorbing a very high energy photon. From these reactions, some variations in the fission mechanism may be expected to produce slightly different fission fragments than those produced by neutrons.

Only three isotopes are classed as fissionable materials namely $_{92}U^{233}$, $_{92}U^{235}$, $_{94}Pu^{239}$, although almost any isotope of atomic number greater than 90 can be fissioned by some means. The term, fissionable material, as it is used today, refers to isotopes which undergo fission by neutrons with a high cross section such that the materials can be used as atomic explosives. U^{233} and Pu^{239} are not naturally occurring isotopes but must be manufactured by a neutron bombardment.

Ordinary uranium consists of three isotopes 234, 235, and 238, and is chiefly U^{238} with the other isotopes being present as follows:

TABLE IV

Uranium isotope	Relative abundance	Percentage abundance
238	1	99. 28
235	1/239	. 710
234	1/17, 000	. 006
---	---	100

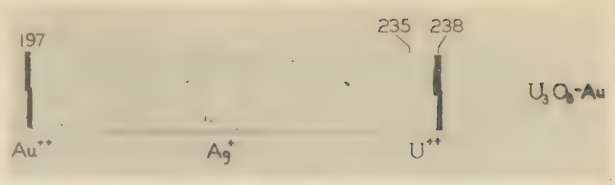

FIGURE 8–6.—Uranium mass spectrum.
Photograph by Prof. A. J. Dempster

Figure 8–6 shows the first mass spectrogram taken of uranium by Dempster in 1935. Here the 235 isotope is faintly visible but U–234 is not apparent on the photograph. The fissionable U–235 isotope can be separated from U–238 by physical methods. Uranium from which U–238 has been removed is said to be *enriched uranium*. Through the use of electromagnetic separation and diffusion processes, this enrichment can be carried out until any desired U^{235} content is reached. These separation processes are extremely difficult and costly operations and during the last war were carried out at Oak Ridge, Tenn. No detailed discussion of these processes is given here. In the following sections when the term pure U–235 is used it will mean U–235 which has been completely separated from U–238.

8.08 Fission Products and Radioactivity

Consider a symmetric fission of the $_{92}U^{236}$ compound nucleus into two fragments of equal mass. This process is diagrammatically illustrated in figure 8–7.

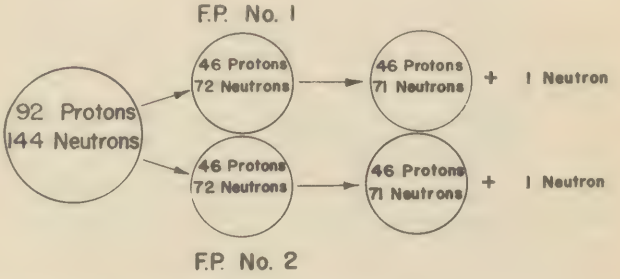

FIGURE 8–7.—Nuclear constituents of fission products

Each fragment will then have mass 118 which will be comprised of 46 protons and 72 neutrons (a palladium nucleus). There will be an instantaneous emission of two neutrons (on an average), and the resultant fission products will be $_{46}Pd^{117}$. Now natural palladium has the majority of its isotopes bunched around mass 107 and its heaviest

isotope is $_{46}Pd^{110}$. Therefore these super-heavy $_{46}Pd^{117}$ atoms formed in fission must be unstable.

It is therefore logical to suppose that the isotope 117 would reach stability by β-emission, thus making up the proton deficiency of the nucleus. This can be easily visualized by referring to the stability curve given in figure 8–8. On the curve, *A* represents the U^{236} compound nucleus. *B* represents the $_{46}Pd^{117}$ nuclei as they are formed in fission. These fission products lie far off the stability curve and to reach it they must emit on an average of from 3 to 4 β-particles as indicated by the short arrows in figure 8–8. The processes whereby a fission fragment undergoes successive beta disintegration and produces a series of new fission products are known as a *fission chain*.

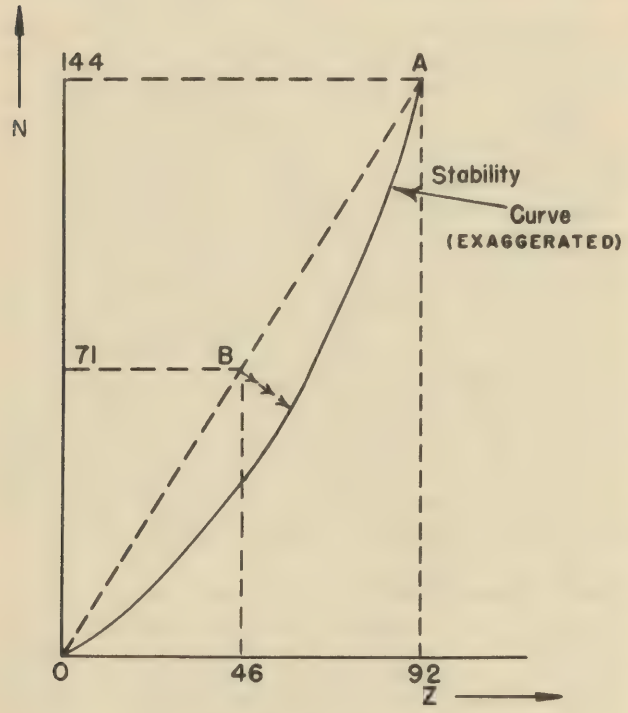

FIGURE 8–8.—Fission products and the stability curve.

The various isotopes found among the fission products are listed in Appendix I—"Nuclei Formed in Fission: Decay Characteristics, Fission Yields and Chain Relationship." Figure 8–9 shows the yield of fission products as a function of mass. Two groups of fission products are formed. A heavy group has a maximum at about mass 139, and a light group a maximum of mass 95. The term *fission yield* refers to the percentage of any fission isotope to the total number of atoms fissioned. Except for their extreme neutron/proton ratios, the fission product isotopes are no different from radioisotopes produced by other means. Many of them are identical with radioisotopes produced artificially, and in fact many of the fission products were first identified by their characteristic half-lives.

In addition to the β-particles and γ-rays which are emitted by the fission products, neutrons are also known to be emitted for as long as several seconds after fission has occurred. These are spoken of as delayed neutrons in contrast to the prompt neutrons which are emitted within 10^{-12} seconds after fission. Delayed neutrons make up only 6/10 of 1 percent of the total neutrons emitted and fall in several groups having different half-lives. Most of these delayed neutrons are emitted within 0.2 seconds after fission but a few (0.02 percent of the total) have a half-life of about 1 minute. It is not too difficult for neutron emission to occur in these nuclei which have an abundance of neutrons. In fact, the energy released by beta decay is sometimes comparable to the binding energy of a neutron to moderately heavy nuclei in the fission product region. While these delayed neutrons are of great practical importance in atomic power, they constitute such a small fraction of the fission neutrons that further discussions will not deal with them. From the standpoint of atomic energy the number of fission neutrons emitted per neutron absorbed is of enormous importance. While the exact value for this number is still secret, the figure averages somewhere between 1 and 3 neutrons per fission. The number is given the symbol η.

8.09 The Chain Reaction for Fast Neutrons

Suppose one has available a small sphere of pure U–235. Now since each fission of a U–235 nucleus produces at least two neutrons, it might be imagined that these fission neutrons would strike other U–235 nuclei and cause them to fission. Such being the case, it is entirely possible that this process may multiply itself very rapidly and fission a great many of the nuclei before the heat generated by the fission products would blow the sphere apart. This multiplication process is called a "chain reaction," and is illustrated in Figure 8–10. Some neutrons will be lost from

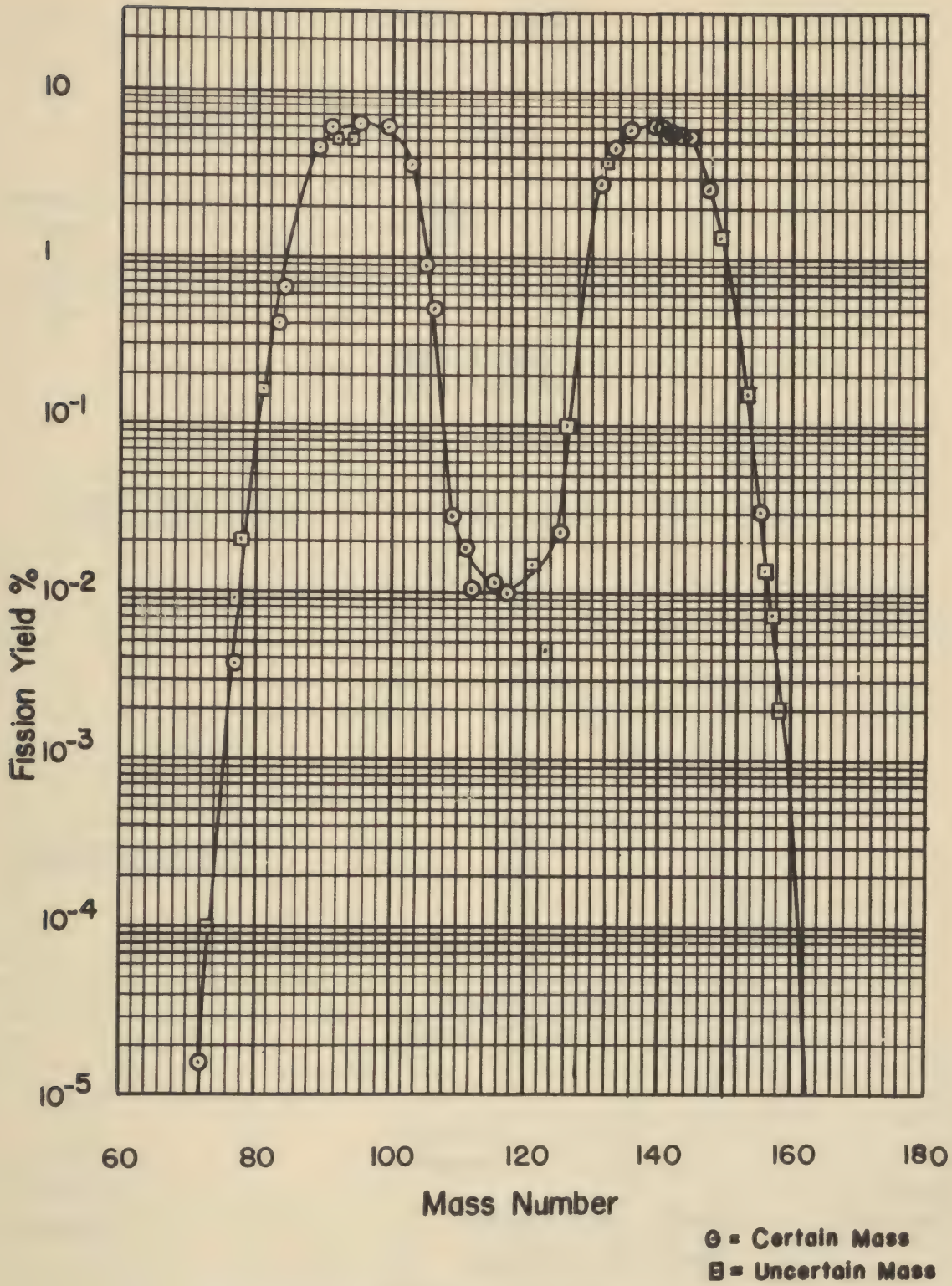

FIGURE 8–9.—Mass distribution of fission products.

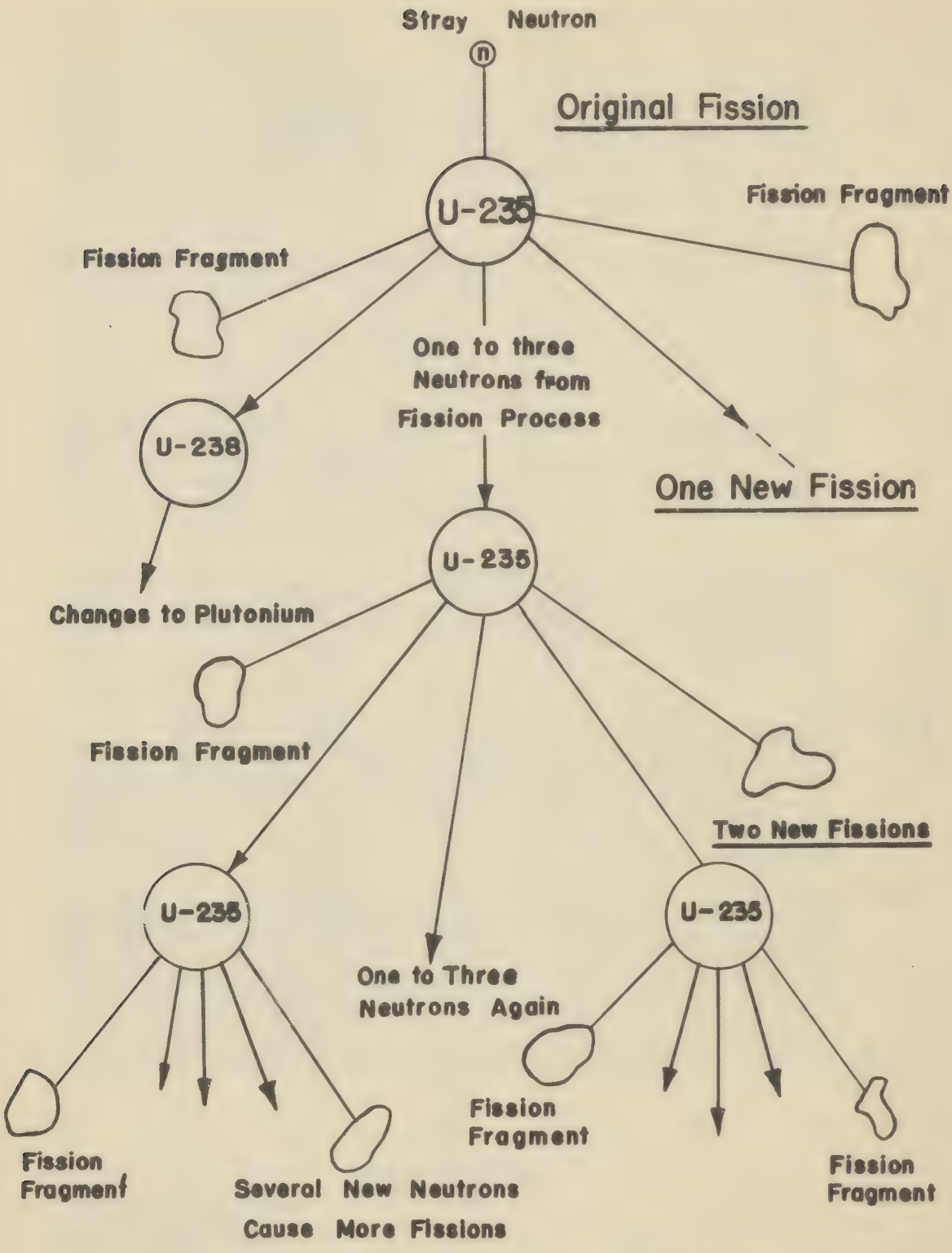

FIGURE 8–10.—A diagram of chain reaction in U^{235} (fast fission).

the system so the reaction will be self-perpetuating only if the number of neutrons produced by fission is greater than the sum of the neutrons producing the fission and those lost. One loss can be minimized by using very pure U–235 so that no non-fissionable elements capture neutrons. A second loss depends on the size of the system. For a sphere, the production of neutrons will be proportional to the number of atoms in it, and therefore to its volume and mass. The escape of neutrons, on the other hand, will be proportional to the surface area. As the size of the sphere is increased, the escape of neutrons becomes relatively less important until a certain critical mass is reached at which the reaction is just self-perpetuating. Smaller masses than this are called subcritical and larger overcritical. Once the critical size is exceeded, the number of neutrons will multiply very rapidly and an explosion will result if this occurs under the proper conditions. If, however, the system should be just overcritical and there were no restraining forces keeping it in a small volume, it would create a flash of neutrons, heating up the mass until it expanded to a new size. This would be subcritical, and the reaction would cease.

It should be emphasized that the ultimate source of energy, whether released in bomb-form or in a power plant, lies in the kinetic energy of the fission fragments. These fragments flying apart with high velocity constitute a heat source of high temperature, measured in millions of degrees. It is this thermal energy that accounts for the explosive effects of an atomic bomb, just as it is also the reason why atomic power is produced. This concept is very simple and it should be clear that there is nothing mysterious about atomic energy. The essential difference between an atomic bomb and an atomic power plant is that in the former the energy is uncontrolled and released in an extremely short time, whereas in the latter, the energy is controlled and released over a period of years.

8.10 The Atomic Bomb

A logical way to assemble an atomic bomb might be to take two hemispheres, each of which is subcritical, and bring them together very quickly. A mechanism which would accomplish this is illustrated in figure 8–11. One hemisphere of

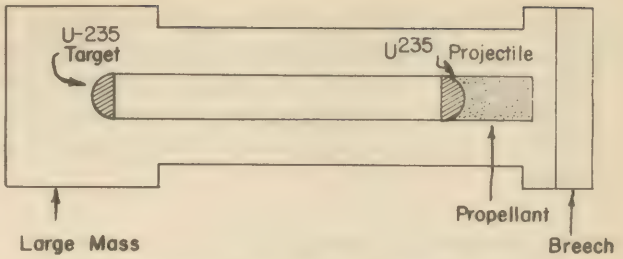

FIGURE 8–11.—An atomic bomb.

pure U–235 is imbedded in a large mass of material (tamper) placed at the target end of the gun barrel. At the other end might be a hemisphere to serve as a projectile. Separated by the length of the barrel, each subcritical mass would be safe, but by firing the projectile down the barrel it would attain high velocity and weld itself together with the target into an over-critical mass. The heavy tamper together with the inertia of the projectile would serve to keep the over-critical assembly together until a large number of atoms were fissioned. This would insure a high efficiency in the reaction. When talking of the *efficiency* of an atomic bomb, the term means the percentage of the fissionable material which is fissioned in the explosion. The explosive force of an atomic bomb has been publicly stated to be equivalent to about 20,000 tons of high explosive. From this fact the number of curies associated with an atomic explosion can be readily and directly calculated. The radioactivity is thus found to be equivalent to that of thousands of tons of radium. Such is the truly fantastic radioactivity associated with atomic bomb detonations. Furthermore, the neutrons produced by the fission may escape and add to this radioactivity either by inducing an (n, γ) or similar reaction in surrounding material, or by directly passing through material and causing ionization from proton recoils.

If instead of considering the radioactivity associated with this hypothetical bomb, one investigates the power output from it, the figures obtained are equally astronomical. This figure may be obtained by multiplying the number of fissions by the energy released per fission. About 2×10^9 kilowatt hours of energy would be liberated. Furthermore, this energy would be liberated extremely fast and thus magnify the explosive effect. The effect of releasing such enormous energy in such a short time interval is that the

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relatively small amount of material is converted into a gas at a temperature of several million degrees. By virtue of its temperature, the gas expands rapidly as a ball of fire producing a blast or shock wave which moves with supersonic velocity.

8.11 Resonance Capture in U^{238}

Besides releasing energy with explosive violence, nuclear reactions can be carried out under controlled conditions in order to be useful for power. In the course of the foregoing sections, there has been no real explanation why fast fission cannot be used to start a chain reaction in natural uranium or, in other words, in U^{238}. The reason is that while fast fission does occur in U^{238}, there is also a competing absorption process which captures fast and other neutrons. This capture robs the system of neutrons and effectively prevents realizing a chain reaction in pure U^{238}. For this reason U^{238} is not classed among the three fissionable materials.

Even though natural uranium contains only a small amount of U^{235}, this amount is significant because of the relatively high fission cross section of U^{235} for slow neutrons. One might therefore hope that this small fraction of fissionable material would permit natural uranium to be used in a thermal fission chain reaction. The advantage to this scheme would be that while it would not lend itself to a bomb-type application, it might be useful for power production or as an intense neutron source to produce radioisotopes. If it had been possible to produce U^{235} economically and in large quantities in 1943, the Manhattan Project would never have attempted to build the large thermal *reactors* (chain reacting-controlled systems) which were constructed at Oak Ridge, Tennessee and Hanford, Washington.

The reason why these large reactors, technically called *piles*, were built was that there was no assurance that Oak Ridge could produce pure U^{235} in time to be of military use in the war. A part of the Manhattan Project, was assigned the mission of building piles for the purpose of utilizing the resonance capture phenomenon in U^{238} and thus producing a new transuranium element which might be used in place of U^{235}. The resonance capture process for U^{238} can be written as:

$$_{92}U^{238} + {}_{0}n^{1} \rightarrow [{}_{92}U^{239}] \xrightarrow{23 \text{ min.}} {}_{93}Np^{239} + {}_{-1}e^{0} \quad (8)$$

The transuranium element 93 is called neptunium. It is produced by the beta-decay of the compound nucleus $_{92}U^{239}$ which has a half-life of 23 minutes. Neptunium is itself unstable and undergoes beta-decay with a half-life of 2.3 days to form element 94—plutonium. This reaction is:

$$_{93}Np^{239} \xrightarrow{2.3d} {}_{94}Pu^{239} + {}_{-1}e^{0} + h\nu \quad (9)$$

From small-scale experiments carried out with microscopic quantities of Pu^{239} produced by cyclotron bombardment of uranium with deuterons, it was shown that plutonium is a fissionable material just as U^{235} is fissionable. Since this new element has a different chemistry from uranium, it is possible to separate it from bombarded uranium by chemical treatment—a process vastly simpler than trying to separate U^{235} from U^{238} by physical means.

8.12 The Slowing Down of Neutrons

In order for the chain reaction to occur in a natural uranium system it is necessary that some of the neutrons be slowed down to thermal energy. However, the resonance capture by U^{238} has to be partially circumvented in order to obtain thermal neutrons. Furthermore, any impurities in the system, such as boron and other neutron absorbers, have to be eliminated in order to obtain thermal neutrons once the resonance capture by U^{238} has been overcome.

To accomplish this objective, Fermi suggested that a lattice of natural uranium and some light element be used for the reacting system. Certain light elements, such as carbon, beryllium, and heavy water, have the property of not readily absorbing neutrons by capture, but they do undergo elastic collisions with neutrons. These substances are known as *moderators*. Suppose elastic collisions between a fast neutron and a large number of carbon atoms be considered. This process is illustrated in figure 8–12.

A fast neutron, such as is produced in fission, comes in at the top of the diagram and is elastically scattered by the carbon nuclei. It undergoes 6 collisions and then is scattered out of the field of view. On the scale of the diagram, only

a few of the carbon atoms are shown and are greatly magnified. The distance between each collision is between 2 and 3 cms.; thus, it is obvious that the carbon is practically transparent to neutrons. At each collision, the neutron loses about ⅑th of its energy. Thus to convert fast neutrons (>1 Mev) to thermal neutrons (1/30 ev) requires that the neutrons make about 100 elastic collisions with the carbon nuclei. Furthermore, during the course of these collisions the neutron must not be absorbed either by U^{238} or by impurities in the carbon.

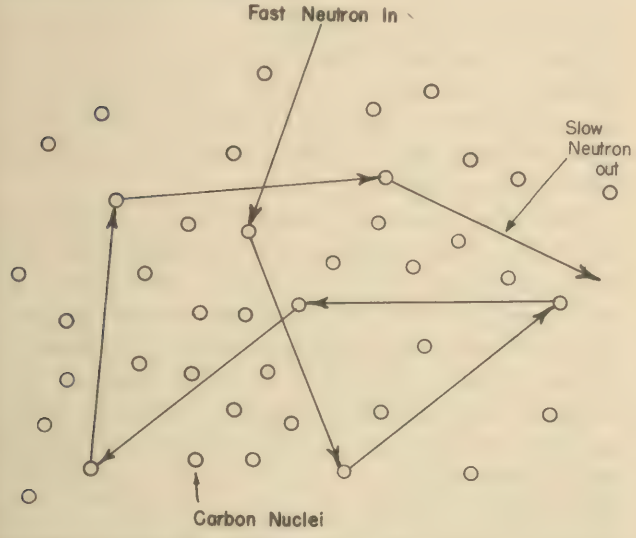


FIGURE 8–12.—The slowing down of neutrons by carbon atoms.

Since the purpose of slowing down the neutrons is to take advantage of the slow fission in U^{235}, there must be some arrangement of uranium and carbon which will permit the reaction to go. However, the problem is not so simple, for it must be remembered that the fissions are only desired in order to produce neutrons to manufacture Pu^{239} by the resonance capture process. Therefore, a balance must be struck in which so many neutrons are reserved for thermal fission, so many for resonance absorption, and a certain number are allowed for loss. The loss may be either by escape from the system, by absorption in impurities in the uranium, or by capture by impurities in the carbon. Figure 8–13, schematically illustrates these processes.

So far as the fission process is concerned, a pile consists of a critical mass of a mixture of a fissionable material and a moderator. The exact size and shape of these materials is a problem that involves many factors, some of which are discussed in the next section.

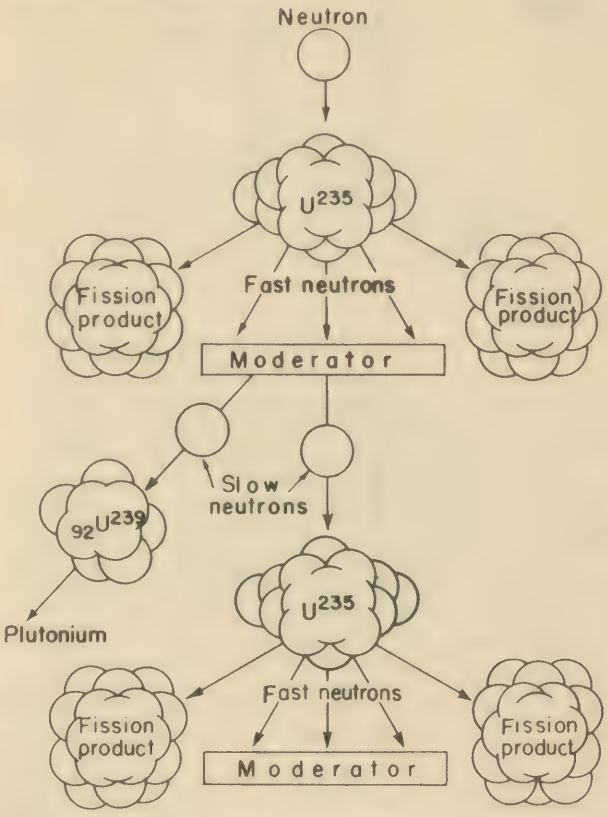


FIGURE 8–13.—Diagram of chain reaction using a moderator.

8.13 Piles

Two piles will be considered. The first is the pile designed to produce plutonium, and the second is the type designed to produce power. Of the first type, the carbon-natural uranium pile will be considered.

(*a*) *Plutonium production pile.*—Thermal neutron reactors were constructed at Hanford, Washington for the purpose of producing plutonium. Details of construction for these units are still classified, as is the power level of operation; however, the principle may be seen as illustrated in figure 8–14. In this diagram, the uranium is shown in the form of lumps imbedded in graphite blocks which are stacked together to form a critical assembly.

Two cadmium-plated control rods are shown running vertically into the pile. With these rods

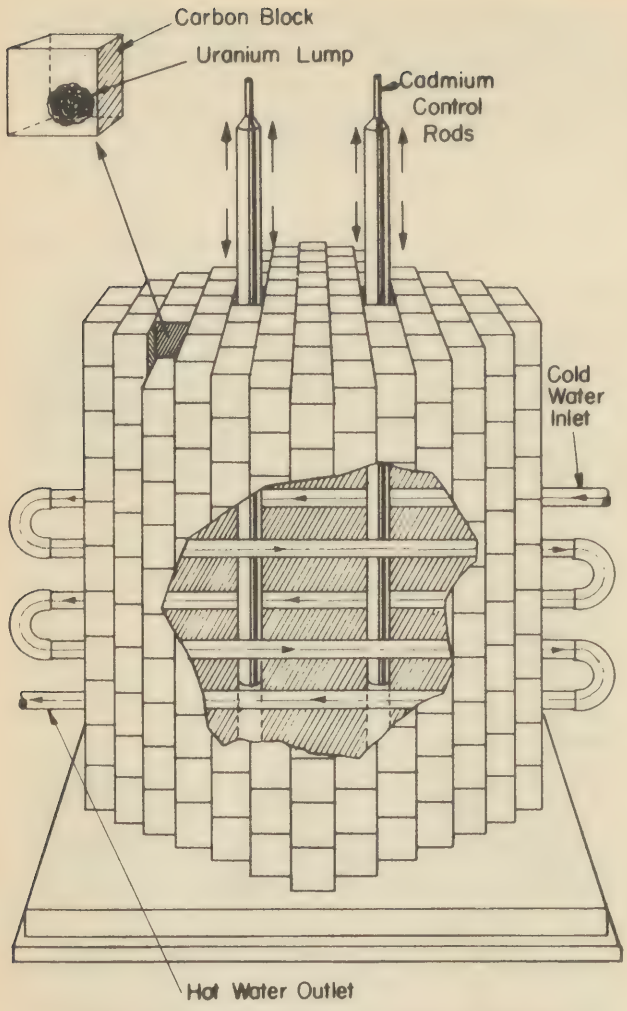


FIGURE 8–14.—Scheme of a uranium carbon pile.

all the way in the pile, the cadmium absorbs the thermal neutrons and the pile will not operate. As the control rod is removed, the pile will reach the critical mass stage and will operate. Thus the pile is an extremely simple machine, for it has no moving parts other than the control rod which is used to start up the pile. Further removal of the control rod increases the neutron flux within the pile and thus increases the power level of operation. As the power level increases, the increased fission rate boosts the thermal energy generated, and unless this excess heat were removed, the pile would soon become dangerously hot. To do this, aluminum tubes are placed inside the reactor and cooling water is circulated.

If the pile were operated at a power level of 100 kilowatts the thermal neutron flux in the unit would be about 4×10^{10} neutrons/cm^2 per second. This would mean that about 4×10^{16} atoms are being fissioned every second. The fission product activity would be equal to about 2.0×10^{6} curies! Two million curies is a fantastic amount of radioactivity, and for this reason piles operating at high power levels require thick shields (not shown in diagram) to prevent the neutrons and gamma rays from injuring personnel working in the vicinity.

If 4×10^{16} atoms are fissioned per second, then 1×10^{16} atoms of plutonium will be formed every second. In 1 day, $86{,}400\times10^{16}$ Pu atoms will be formed—this would be equivalent to about 0.3 grams of plutonium per day. These figures are all hypothetical and are without factual basis; they are used only to illustrate the order of magnitude of pile reactions.

The actual plants at Hanford use the uranium in the form of aluminium jacketed slugs which can be easily removed from the pile. Once the neutron irradiation of each slug has proceeded to a point where there are significant quantities of plutonium in it, the slug is removed from the pile, allowed to decay for some time so that its radioactivity decreases, and it then undergoes the chemical processing. Even for long neutron irradiations, the relative proportion of Pu^{239} in the uranium slug is small and has to be recovered by special techniques.

Every thermal pile, whether it is designed for plutonium production or for power production, has certain basic requirements which can be summarized as follows:

(1) Critical size must be attained.
(2) An efficient moderator must be used.
(3) Pile controls must be suitably designed.
(4) Provision must be made for adequate cooling.
(5) The fissionable material must be replaceable.
(6) Proper shielding is necessary.

(*b*) *Power pile.*—Figure 8–15 shows a diagram of the Daniels power pile which is to be built at Oak Ridge. It differs from the pile described above in that it is a high temperature reactor from which heat is extracted to run a conventional power source. Much has been said about atomic power and many misconceptions are current.

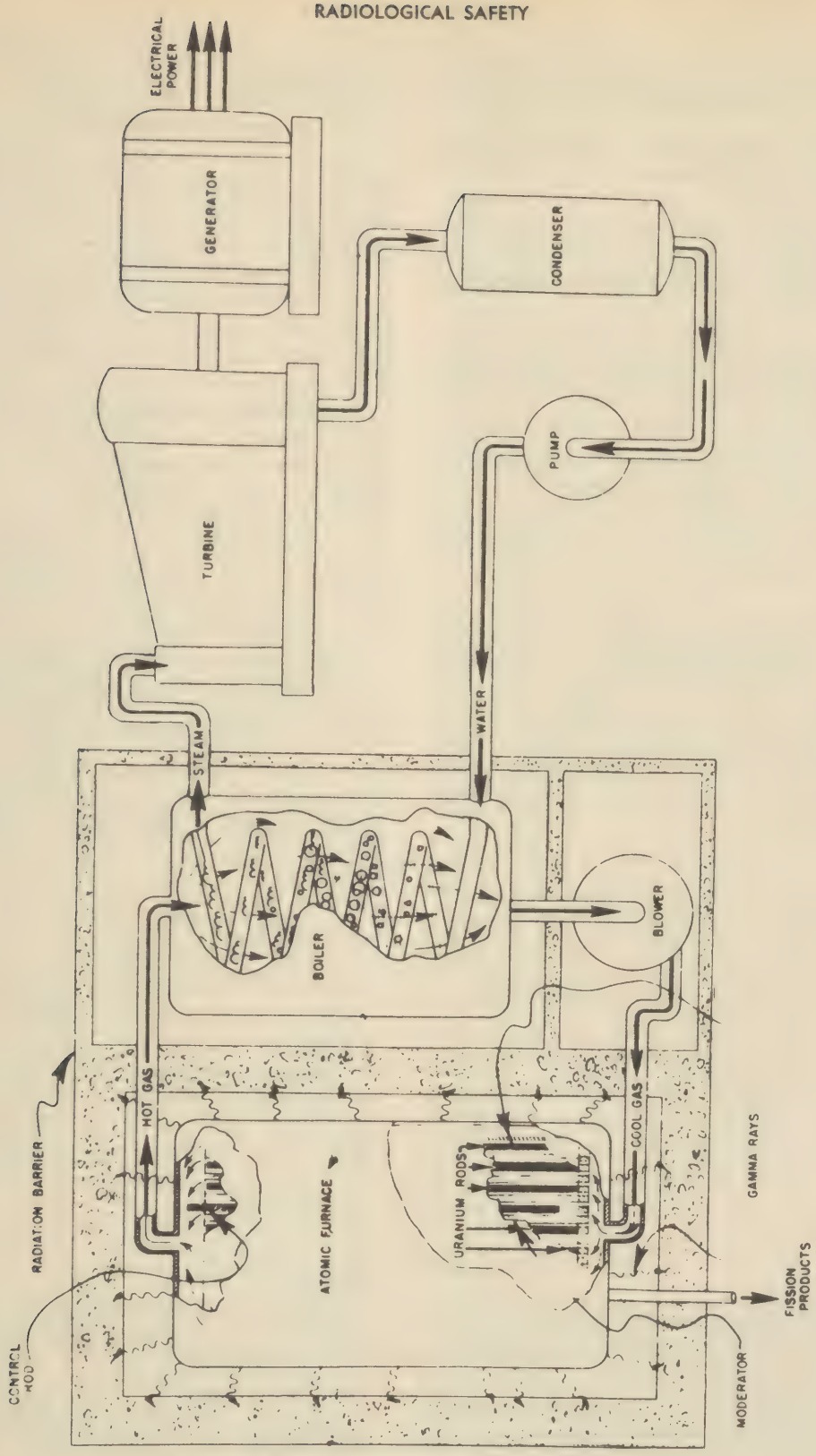


FIGURE 8–15.—Daniels atomic power plant.

Rather than discuss the Daniel's pile in detail, the following facts about atomic power are summarized:

(1) The highest temperature at which a power pile may be operated is determined by the properties of pile materials.

(2) A power pile cannot be operated indefinitely without recharging the unit with fresh fissionable material to replenish that which has been depleted by fission.

(3) The process by which the heat energy generated in the pile is converted into useful power is exactly the same as in an ordinary power plant. Conventional heat exchangers, condensers, and blowers are used just as illustrated in figure 8–15.

(4) Every atomic power plant will produce radioactivity in proportion to the power output of the machine. For this reason, special shielding and health precautions are absolutely essential for pile operation.

(5) No atomic power plant can operate unless it contains a certain critical mass of fissionable material. Because of this fact, together with the fact that many tons of shielding and conventional power equipment are needed, atomic power plants will not be readily adaptable for anything except fixed or large mobile installations such as naval vessels.

(6) Until these new type power units have been built and successfully operated for considerable periods of time, no evaluation of the relative cost of atomic power to ordinary power can be made. The immediate prospects are not such as to encourage one to believe that atomic power will supplant existing power resources during the next several decades.

8.14 The Transuranium Elements

Both the transuranium elements neptunium 239 and plutonium 239 have already been mentioned. Plutonium is an alpha emitter with a half life of 24,000 years, and is of prime importance because it fissions with slow neutrons just as does U–235. Other isotopes of these two elements can be produced by artificially accelerating light particles and bombarding uranium with them.

In addition, isotopes of elements 95 and 96 have recently been announced. Element 95 is called americium and is abbreviated Am. Its single isotope is at mass 241, is an alpha emitter, and has a half life of 500 years. Element 96 has been named curium (Cm) and to date has two isotopes, one of mass 240 and another of mass 242. Both are alpha emitters and have half lives of 1 and 5 months respectively.

The transuranium isotopes are shown in table V.

In this table, the symbol with the half-life figure denotes the type of decay scheme for each isotope. K indicates decay by K electron capture. Not indicated in this chart is the U–233 isotope which is produced by neutron absorption in thorium 232. This reaction leads to two subsequent beta decays forming $_{92}U^{233}$, which is an important isotope by virtue of the fact that it undergoes slow fission.

There are thus three fissionable isotopes which are important for power or military application—$_{92}U^{233}$, $_{92}U^{235}$, and $_{94}Pu^{239}$.

TABLE V

Mass number	234	235	236	237	238	239	240	241	242	Chemical symbol
Curium							1 mo α		5 mo α	Cm
Americium								500 y α		Am
Plutonium					50 y α	24,000 y α				Pu
Neptunium	4.4 d K	8 mo. K	20 hr β	2×10^6y	2 d β	2.3 d β				Np
Uranium	2.7×10^5y α	7×10^8y α		6.8 d β	4.5×10^9 y α	23 m β				U

(After Seaborg Science 104, 379 (1946)

Chapter 9

INSTRUMENTATION AND PHOTOGRAPHIC DOSIMETRY

9.01 Introduction

The detection and measurement of high energy radiation depends entirely upon the proper use of suitably constructed instruments since nature has not seen fit to provide man with senses capable of responding to it. Without instruments even intense radiation fields will not be recognized until irreparable damage has been done. It is therefore of utmost importance that all persons making radiation measurements have a thorough understanding of the principles of operation and the limitations of the available instruments. Furthermore, in making radiation measurements an individual must interpret meter readings in terms of the characteristics of the specific instrument, and serious and dangerous errors can easily be made without a knowledge of the basic principles behind the instrument design. This chapter aims to present briefly the underlying principles, design characteristics, and limitations of the types of instruments at present available.

9.02 Ionization of Gases

If photographic film and a few special methods are excepted, all detecting devices are based upon the ionization produced in gases by the incident radiation. When an ionizing agent, such as an alpha particle or a photon of electro-magnetic radiation, enters a gas, it may act on a neutral atom or molecule with a force large enough to remove one or more electrons from the atom. It is most probable that two ions will be formed, and so it is customary to speak of the formation of *ion pairs*. This process must be carefully distinguished from pair production, where an electron and a positron are born out of annihilation of a high energy gamma ray (ch. 5, sec. 5.10).

When the total energy of an ionizing radiation is known and the total number of resultant ion pairs is determined, it is found that the energy lost per ion pair is considerably greater than the ionization energy. This is due to the fact that some collisions occur without ionization but with an energy loss to the ionizing agent. Moreover in some collisions a more tightly bound inner electron will be removed, and this will require more energy than the ionization energy, which refers to the most loosely bound electron. The average energy loss per ion pair in air is about 33 electron volts. Hence an incident particle having an energy of 1.5 Mev will produce in air $1.5\times10^6/33$ or 4.5×10^4 ion pairs. The total number of ions produced will be twice this figure.

The production of ionization by a high-speed particle has been used in the Wilson cloud chamber to make visible the path of the particle. The cloud chamber is an invaluable tool in nuclear research and as such merits a brief description even though its use is confined to physics laboratories. The cloud chamber utilizes the fact that water vapor will not readily condense to form visible rain droplets unless there is a nucleus of some sort to collect around. Charged particles or ions are very acceptable nuclei for droplet formation. In the chamber water vapor is produced in a cylinder closed at the top with a glass plate for viewing and at the bottom with a tight-fitting piston. A small amount of water is put on top of the piston. If the piston is suddenly withdrawn, the gas will expand and cool. It will be supersaturated, that is it will contain more water than it can hold at the reduced temperature. Conditions are therefore favorable for droplet formation with a subsequent raining down of the droplets into the excess water on the top of the piston. If ions are present along the path of an incident particle, the water droplets will form about these ions and will be visible as a series of tiny beads of water. This is the only available method by which particle tracks in air can be made visible, and it has yielded a wealth of valuable information. Space does not permit a full description of its many applications to nuclear research, but some typical tracks in a chamber are shown in figure 9–1.

9.03 Ionization Currents

If ions are formed in a gas subject to an electric field, they will move in opposite directions, the negative ions toward the positively charged anode and the positives toward the negatively charged cathode. The speed attained by the ions depends on the voltage applied to the electrodes, the nature

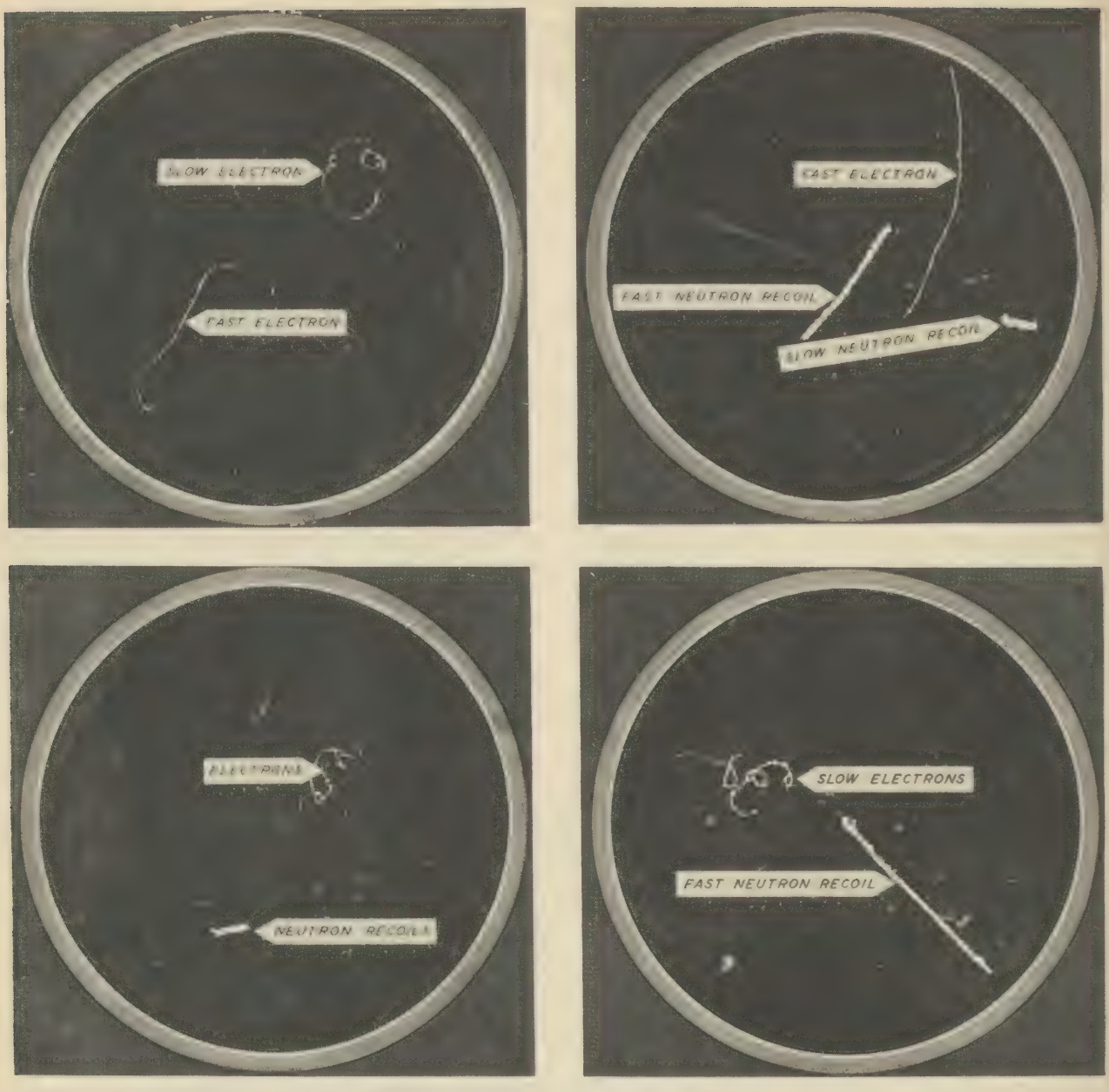


FIGURE 9–1.—Visible path of nuclear particles in Wilson cloud chamber.

Courtesy Carnegie Institute of Washington, Department of Terrestrial Magnetism

of the ions, and the gas pressure. If the electrodes are connected to a battery, the ions reaching the electrodes will give up their charge and become neutral again at the expense of removing charge from the battery. This results in a current flow through the battery and the external circuit. In general this current flow will be extremely small, and special measuring devices are required to detect it. As an example consider the ions produced by the 1.5 Mev particle previously discussed. This particle left a trail of 4.5×10^4 ion pairs, each ion having a charge of 1.6×10^{-19} coulombs. For each ionizing particle the charge that has been separated will be $4.5\times10^4\times1.6\times10^{-19}=7.2\times10^{-15}$ coulombs. Assuming 100 such α–particles entering the gas per second, the total charge flowing will be $100\times7.2\times10^{-15}$ coulombs per second or 7.2×10^{-13} amperes. Portable

microammeters can scarcely detect currents smaller than 10^{-6} amperes, and the best laboratory galvanometers are sensitive to about 10^{-10} amperes. Thus ordinary current measuring instruments are obviously inadequate for work with such ion currents.

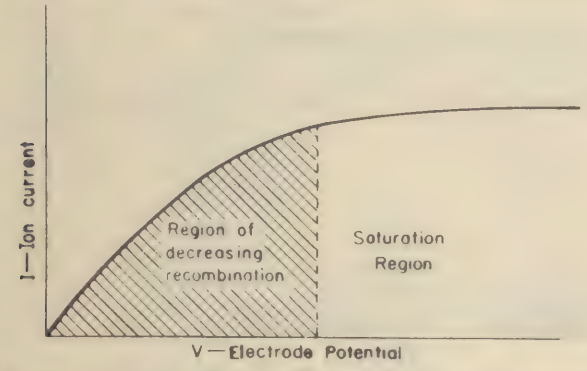


FIGURE 9–2.—Variation of ion current with potential applied to collecting electrodes.

When a constant amount of ionization is produced, as by a constant intensity X-ray beam, and when the ionization current is measured for various voltages applied to the collecting electrodes, a relation similar to that shown in figure 9–2 is obtained. With low collecting voltages the ion velocities are low, and considerable time is required for them to reach the electrodes. Because of the mutual attraction of oppositely charged particles there is always a tendency for ions to recombine and form neutral atoms. Any ions which recombine do not contribute to the externally measured ion current since they are neutralized before they reach the electrodes. The chance of recombination is greater the longer the time before the ions reach the electrodes. Thus with low collecting voltages there is a substantial amount of recombination, and many of the ions are lost before they can contribute to the ion current. The fraction lost decreases with increasing voltage, and eventually all of the ions are collected so there is no further increase in current. This condition is known as saturation, and the maximum current is called the *saturation current*.

It is obviously desirable to work with saturation currents whenever possible. This condition will yield the maximum current that can be obtained from a given amount of ionization. Furthermore in the saturation region the current is independent of the electrode voltage, and hence fluctuations in this voltage will not affect the current readings. This is particularly important in portable instruments where it is not possible to incorporate elaborate voltage regulating circuits and where battery voltages will change with use.

An ion will move with an increasing velocity and energy until neutralization occurs or until it loses energy through collisions with gas molecules. If the mean free path (chap. 2, sec. 2.07) is small and the collecting voltage is not too high, the ion will gain only a small amount of energy between collisions. At each collision it will share its kinetic energy with the struck gas molecule in such a way that both kinetic energy and momentum are conserved. Such collisions are called elastic and are analogous to the collisions of billiard balls.

If the mean free path is increased and if the applied voltage is high, the ion will gain a greater energy between collisions. When an ion has an energy greater than the ionization energy of the gas molecule, it may produce secondary ions upon collision. The total kinetic energy after the collision will be less than the total kinetic energy before by the amount of energy expended in producing the ion. In this type of collision kinetic energy is not conserved, and the process is called inelastic.

The secondary ions formed by inelastic collisions will in turn be accelerated by the electric field and may produce further ionization. This cumulative effect is known as Townsend or *avalanche ionization*. If a total of A ion pairs results from one original pair, the process is said to have a gas amplification factor of A. In practice A varies from about 10 in gas-filled photoelectric cells to 10^8 in some Geiger-Mueller counter tubes. Avalanche ionization is discussed in greater detail later in this chapter.

9.04 Electroscopes and Electrometers

Instruments for measuring the amount of electric charge collected in an ionization chamber are known as electroscopes and electrometers. It is sometimes difficult to classify an instrument as one type or the other, but for present purposes an electroscope will denote an instrument which does not require a continuous external voltage for its operation.

The *Lauritsen electroscope* is one of the most

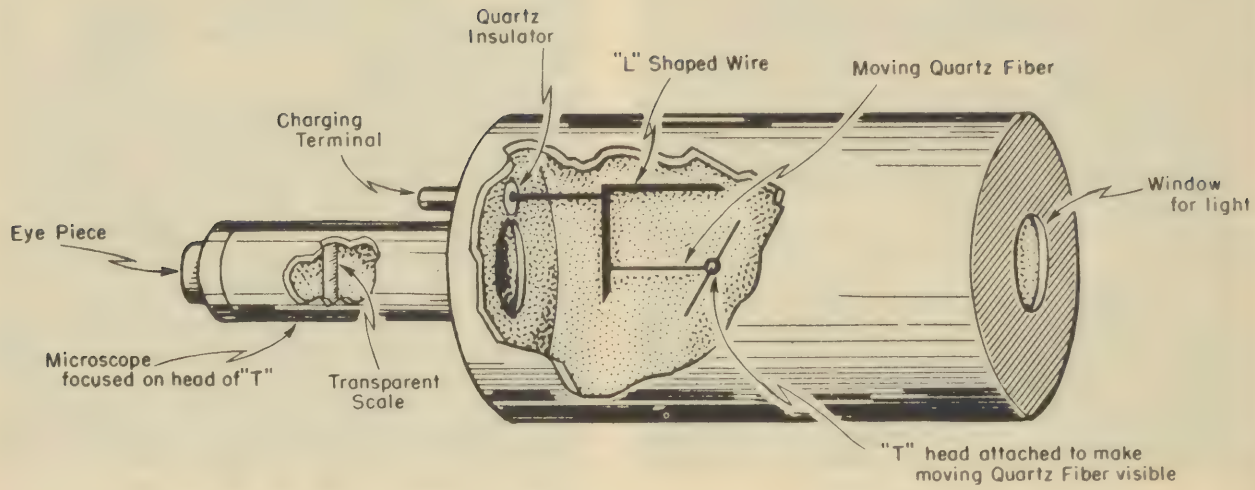


FIGURE 9–3.—Schematic diagram of a Lauritsen electroscope.

generally useful instruments for radiation measurements. In this instrument a wire is bent into the form of an L and mounted on the electroscope case through an insulating bead of quartz or amber (fig. 9–3). The moving system is a quartz fiber about 5 microns in diameter, made conducting with a thin metal coating and cemented to one arm of the L. To make this fiber visible in the microscope a second quartz fiber is fused to the free end of the first, and at right angles to it to form a T. The microscope is focussed on the head of the T using light admitted through a small window in the end of the electroscope case. The L and the conducting fiber form a single conductor which is charged by moving a wire from a battery into contact with one arm of the L. The mutual repulsion causes the quartz fiber to deflect from the side of the L. Ions formed inside the case will neutralize the charge and the fiber will return toward its uncharged position. As in other electroscopes the deflection is not linear with charge and deflections must always be taken over the same scale range.

Another useful quartz fiber instrument is the pencil type electroscope, or *dosimeter* (fig. 9–4). This is essentially a Lauritsen electroscope modified so that the entire instrument is about the size of a large fountain pen. The conducting system in the dosimeter consists of two quartz fibers each bent into a *U*. The two fibers are fused together at the ends of the *U*, and the mircoscope is focussed on the end of one fiber. A charge placed on the fiber system causes the fibers to diverge by mutual repulsion. The protective cap on the end of the pencil meter has a small window for illuminating the fiber and the scale. When the cap is removed, a contact is exposed for charging the fiber system from an external battery. Instruments of this type can be made sufficiently rugged to withstand the shocks of normal human activity, are small enough to be worn comfortably, and are very useful for measuring integrated exposures. They can be made with a sensitivity such that 0.1 roentgen will produce about one half of full scale deflection.

Electrometers also measure electric charge through the action of electrostatic forces on a fiber or a light conducting vane. By applying an external potential to auxiliary electrodes, a somewhat greater sensitivity can be attained than is usual for electroscopes. Many types of electrometers have been developed but it is not possible to discuss them here in detail. They are essentially laboratory instruments and are particularly suitable for measuring low energy beta or alpha particles.

Before leaving the discussion of electroscopes and electrometers a few general considerations of use and operation should be mentioned. In the

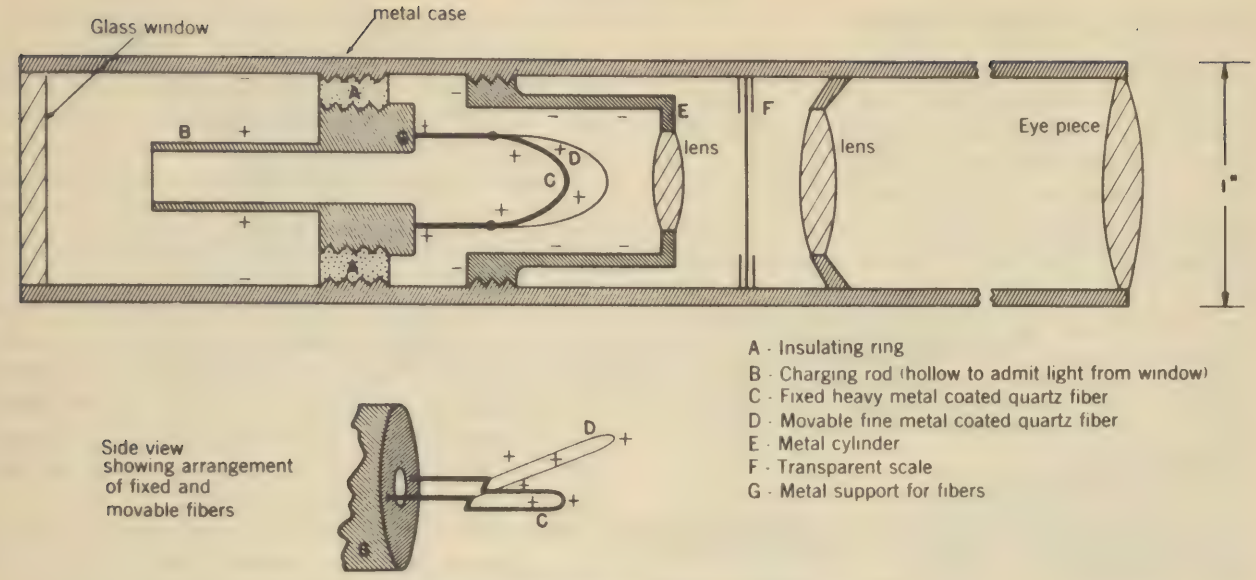


FIGURE 9–4.—Pocket dosimeter electroscope.

construction and use of these instruments the utmost care must be taken to maintain a high electrical resistance in all insulators. Only the very best insulators, such as amber, quartz, sulphur, or polystyrene, are suitable, and these must be kept free from dust, moisture, and handling if satisfactory operation is to be obtained. This maintenance of high insulation is vital because the quantities of electricity involved in most ionization measurements are extremely small.

The minuteness of the electrical quantities involved can be realized from the following considerations: An electroscope can be considered as a condenser with a capacitance C charged to a potential V. The charge Q will be given by the relation:

$$Q=CV \qquad (1)$$

A reasonable capacitance for an electroscope is 10 $\mu\mu$ f (10 e.s.u.). If it is charged to 300 volts (1 e.s.u.), the charge will be 10 statcoulombs or 3.3×10^{-9} coulombs or 2×10^{10} electrons.

In the absence of ionizing radiation a good electroscope should maintain its charge for many hours. Assuming 100 hours as a reasonable discharge time, the maximum allowable leakage current through the insulators can be calculated from the relation,

$$I=\frac{Q}{t} \qquad (2)$$

to be 0.9×10^{-14} amperes. By Ohm's law the resistence must be at least 3.3×10^{16} ohms. Some simplifying assumptions have been made in the above calculations, but they give the order of magnitude of the resistance required in an electroscope to prevent the minute charges usually measured by the instrument from leaking away through the resistance. Anyone who has worked with high resistances will appreciate the difficulty of maintaining these values, particularly under field conditions.

Insulator *soak-in* is a phenomenon regularly encountered in the operation of electroscopes and electrometers. When an instrument has been out of use for some time and is charged, a rather rapid discharge will be noted. This is due to the penetration of part of the charge into the insulator. It is not leakage in the ordinary sense because it practically disappears if the instrument is kept charged for a day or so. To eliminate this the instrument should be charged a day or more before it is used.

It will be noted that the moving part of most electroscopes is a quartz fiber. Quartz is very strong, particularly in small diameters, has a low coefficient of thermal expansion, and has desirable elastic properties so that the fiber will always return to the same zero point. These characteristics make quartz an outstanding material for sensitive measuring instruments.

9.05 Ionization Chamber Instruments

Ionization chamber instruments vary widely depending on the particular type of radiation to be detected. Short range radiation is admitted to the chamber through a suitable window. If alpha particles are to be measured, the window must be exceedingly thin to allow them to enter the chamber. Because of their short range, however, it is certain that once inside the chamber they will expend all of their remaining energy in ionizing the gas. Very few windows are thin enough to admit α-particles, but thin mica or stretched nylon film about 0.0001 inch thick is satisfactory.

If beta particles are to be measured, the windows need not be so thin, and the path of the particle inside may be so long that it is not completely absorbed by the gas and loses a portion of its energy striking the chamber wall. To obtain the greatest possible number of ion pairs, the β-particle should expend its entire energy in the gas. If the chamber is filled with a heavy gas, such as argon under pressure, all but the most energetic β-particles will be absorbed completely in the gas.

Quite different considerations enter into the design of an ionization chamber for measuring very penetrating radiations such as X-rays or γ-rays. When a photon enters the ion chamber and is absorbed by air, high speed electrons are produced. These electrons travel through the gas in the chamber producing ions until their kinetic energy is spent. All of the ions produced must be collected to fulfill the conditions of the definition of the roentgen, and this means that the ionization chamber must be so large that every primary electron loses all its energy before striking the walls. For 0.2 Mev X-rays this requires a chamber about 20 centimeters in diameter. With higher energy radiations the electrons will have higher energies, and the ionization chambers must be made still larger. Such chambers are out of the question for field use, and it is necessary to construct chambers which are much smaller but which are equivalent to the large standard units.

To be equivalent, the small portable chamber should have the same absorption for X- and γ-rays as the air in the standard chamber and should also have the equivalent of the long air paths for the absorption of the high energy electrons. Since the absorption of X- and γ-radiation depends primarily on the atomic number of the absorbing material, it is reasonably satisfactory to choose for the walls of the ionization chamber a material having an atomic number close to 7 or 8, the values for nitrogen and oxygen. Carbon with an atomic number 6 is reasonably close, and chamber walls are regularly made of bakelite or plastics which contain a high percentage of carbon atoms. A thin wall of such material will be equivalent to a large amount of air because the solid has a much greater density and thus has an equal number of atoms packed into a smaller space. Since human tissue is composed chiefly of carbon, oxygen, nitrogen and hydrogen, such an instrument will simulate absorption by the body.

The wall thickness will be a compromise because the optimum thickness depends on the energy of the radiation. Low energy radiation will produce low energy electrons which lose a large fraction of their energy in the walls and hence do not contribute fully to the ionization in the gas. Very high energy radiation on the other hand may produce high energy electrons that leave the chamber and so produce in the gas only a fraction of the ionization of which they are capable. In practice it is possible to build chambers which are satisfactory for X-rays of energies between about 0.08 and 0.25 Mev. These chambers can also be used to measure γ-rays if they are calibrated against suitable standards. Ionization chambers designed on these considerations are known as *thimble chambers*. They are usually made of a bakelite shell with a thin graphite coating on the inner surface to make it conducting and a well insulated central electrode.

One successful thimble chamber instrument is the *condenser r meter* shown in figures 9–5 and 9–6. In this instrument the ionization chambers fit into a bayonet type socket and make connection with the fiber electroscope and charging mechanism. The position of the fiber is read with a microscope and scale illuminated by an internal bulb and battery. With the chamber in position the system is charged by a frictional electricity generator until the fiber is at zero on the scale. The charged chamber can then be removed from the meter and the insulation protected from dust by a metal cap. The chamber may be placed in a desired location or carried by a workman and read at a later date

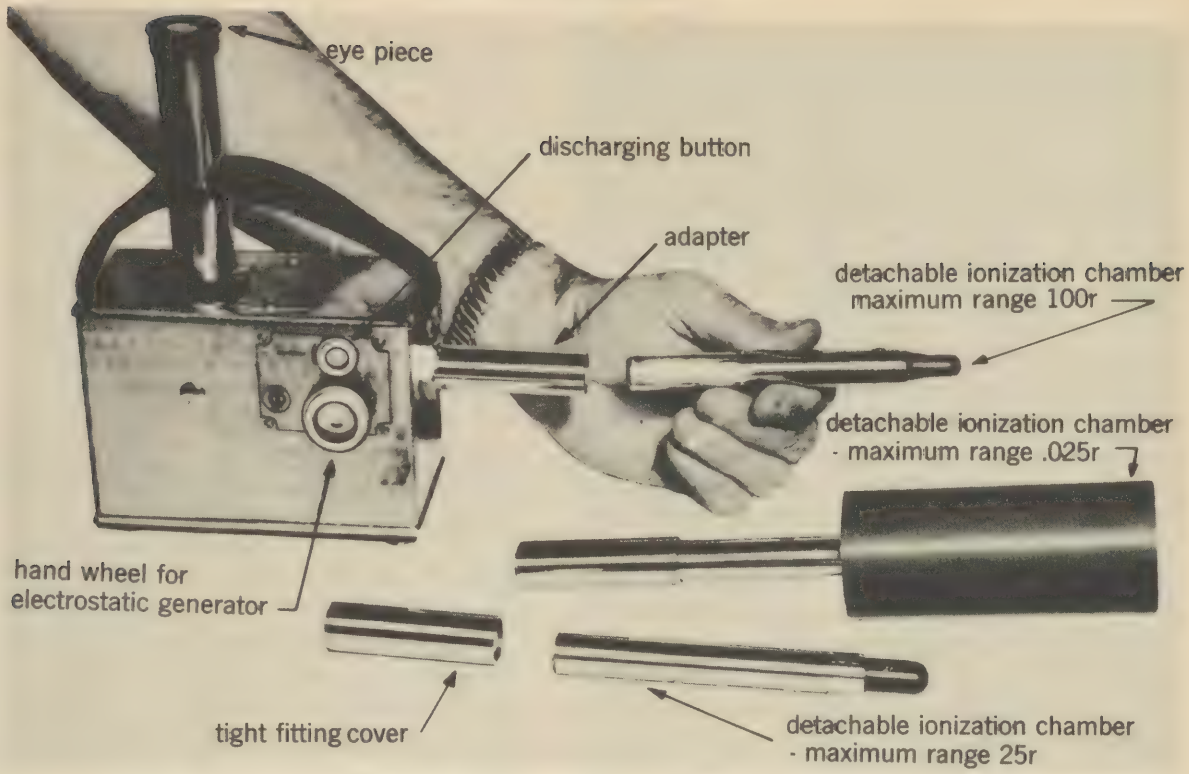
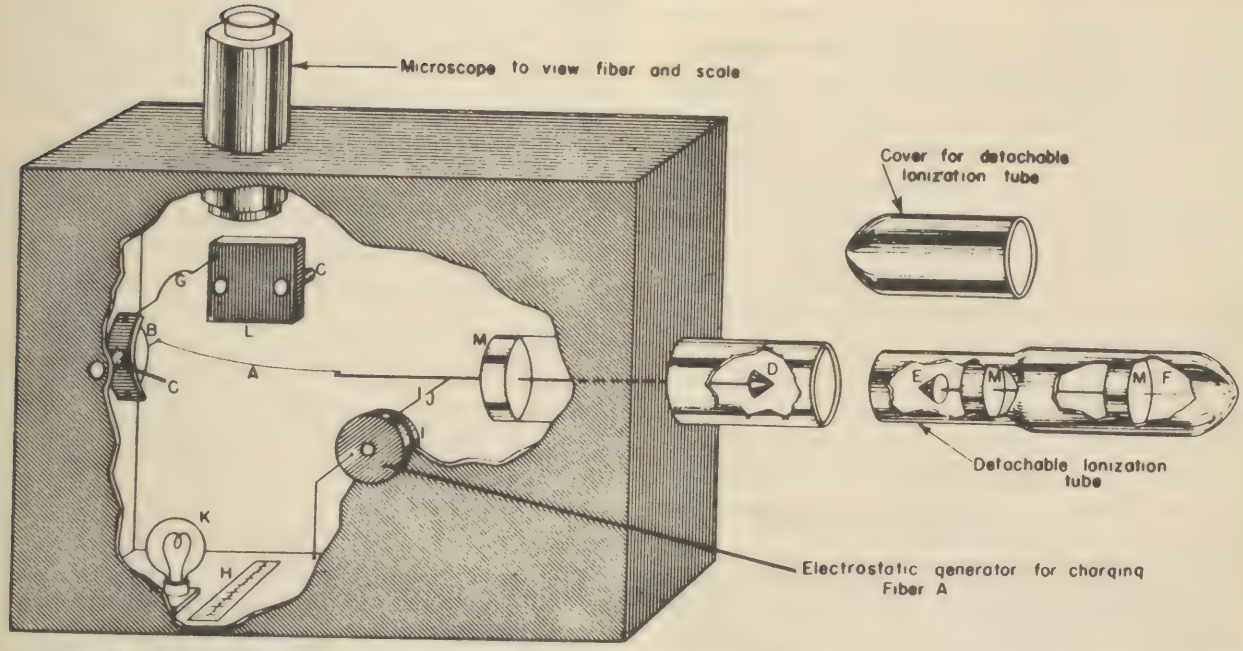


FIGURE 9–5.—Condenser *r* meter.



A - Movable fine quartz fiber
B - Bow to supply tension for fiber A
C - Supports insulating bow B and plate L from case
D and E - Terminals which make contact when detachable tube is inserted in instrument
F - Ionization chamber
G - Conductor between bow and plate placing L and A at the same potential
H - Scale
I - One disc of electrostatic generator grounded to case
J - switch
K - Light to illuminate scale
L - Plate
M - Insulators

FIGURE 9–6—Condenser *r* meter, cut-away view.

by reinserting the end of the partially discharged chamber into the meter socket. The scale is graduated directly in roentgen units with appropriate multiplying factors for the various sized chambers. These are available in sizes from 0.25 to 100 roentgens. The scale reading after exposure will be the total exposure since charging; if the time between readings is known, the average exposure rate can be calculated.

The condenser *r* meter has been used for measuring neutron intensities as well as X- and γ-rays. Neutrons will penetrate the chamber walls, produce ionizing recoil nuclei and discharge the chamber. This meter was used to measure neutron intensities until better methods were developed. An arbitrary unit of neutron intensity, termed the *n* unit, was defined in terms of this meter. The definition of an *n* unit is: If an *r* meter ionization chamber is exposed to a neutron flux and an *r* reading is obtained on the scale, that reading will be numerically equal to the number of *n* units of neutron intensity. This unit is unsatisfactory because of the dependence of ionization on the velocity of the neutrons but is still used to some extent.

9.06 Ionization Chamber—Amplifier Instruments

Although the condenser *r* meter is a very useful instrument, it is not entirely satisfactory for survey purposes since it does not read radiation intensities directly. The chambers must be charged, left in the radiation field for an appropriate time, and then read with the meter. This is quite satisfactory if it is desired to determine the total integrated exposure of an individual whose work requires him to move about in radiation fields of varying intensity, but if a large contaminated area is to be surveyed the number of chambers required becomes exorbitant. This type of work requires an instrument which will give a steady deflection that is proportional to the amount of radiation striking the chamber.

If very sensitive current measuring instruments were available, it would be possible to put one of these in series with the ionization chamber and the battery and measure the current directly. Unfortunately ionization currents are too small to be measured with portable meters, and it is necessary to use other means. If a resistance is put in series with the ion chamber and the battery, there will be a voltage drop across it, which by Ohm's law will be proportional to the ionization current. For example, if the ionization current is 10^{-12} amperes and R is 10^9 ohms, $V=10^9\times 10^{-12}=10^{-3}$ volts. It is perfectly feasible to measure voltages of this order with suitable vacuum tube circuits.

If the resistor in the ionization chamber circuit is incorporated into the grid circuit of a vacuum tube (fig. 9–7), any voltage developed across the resistor will be impressed on the grid and will produce changes in the plate current.

It is possible to obtain vacuum tubes such that a grid voltage change of 1 volt will produce a plate current change of 2,500 microamperes. If a voltage of 10^{-3}, produced by the 10^{-12} ampere current flowing through 10^9 ohms, is put on the grid of such a tube, the change in plate current will be $2{,}500\times 10^{-3}=2.5$ microamperes or 2.5×10^{-6} amperes. The tube, therefore, has amplified a current of 10^{-12} amperes to 2.5×10^{-6} amperes, a gain of a factor of 2.5 million. Since this current is flowing in the plate circuit of the tube which will have a resistance of 10^6 ohms or less, it is no longer necessary to maintain the extremely high insulation resistances demanded in the ionization circuit. Only ordinary insulation values are needed in the plate circuit of the vacuum tube or in any succeeding circuits.

It is necessary, however, to choose the vacuum tube rather carefully if satisfactory operation is to be obtained. In the ordinary vacuum tube there is a small grid current which flows even when the grid is made negative. This grid current is due to several factors, one of which is residual gas becoming ionized in the electron stream. In the average tube this grid current is perhaps 10^{-10} amperes which is negligible for most applications. When the tube is connected to an ionization chamber, this grid current has the effect of shunting the series resistance and thus reducing the sensitivity. Special tubes, known as electrometer tubes, have been constructed for this use. In these tubes it has been possible, by special design and construction, to reduce the grid current to about 10^{-15} amperes which permits quite satisfactory operation with ionization chambers.

In many cases the amplification obtained from a single tube is not sufficient to operate a rugged indicating meter, and further amplification is

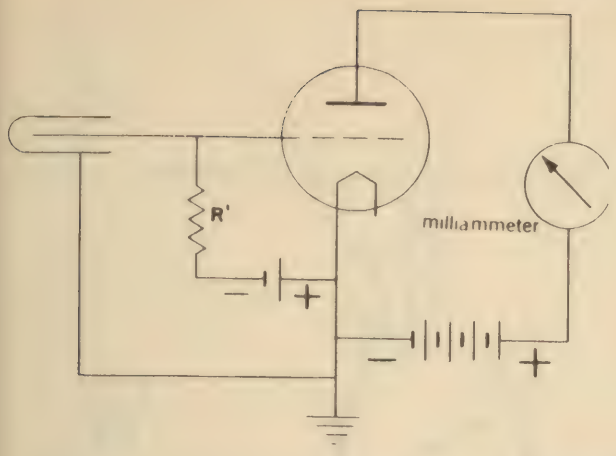


FIGURE 9–7.—Ionization chamber with single stage amplifier circuit.

necessary. In the preceding example the final plate current change was only 2.5 microamperes which is too low to operate portable meters. If a resistance is placed in the plate circuit of the electrometer tube, variations in ion current will produce voltage fluctuations across the resistance. These variations in voltage can be impressed on the grid of a second tube for further amplification.

With no ion current in the chamber there will be a steady plate current in both tubes. In the second tube this steady plate current will produce a steady meter deflection on which the current changes due to amplified ion currents will be superimposed. It is highly desirable to have a meter reading of zero when there is no current (or only that due to background) in the ionization chamber. To accomplish this the auxiliary circuit shown in figure 9–8 can be used. This circuit sends a current through the meter in the opposite direction to the steady plate current and can be adjusted so that the combined currents are exactly zero. If this adjustment is made with the ionization chamber disconnected, the meter will read zero until an ionization current flows. The meter readings will then be proportional to the ionization current.

The calibration of an ionization chamber-amplifier instrument depends on the amount of amplification obtained from the tubes, and hence it is necessary to maintain the amplification as constant as possible. One factor which will affect the amplification is the battery voltage which is applied to the ionization chamber and the amplifier tube. To eliminate this variable, instruments are frequently supplied with a voltmeter and an adjusting rheostat so the voltage can be set to the value it had at calibration.

In general, ionization chamber instruments, particularly those designed for field use, do not have the sensitivity that can be attained by Geiger-Mueller counters. Ionization chamber instruments for field use will detect γ-ray intensities of 0.1 roentgen per 24 hours but are not sensitive much below this. They are more satisfactory for high intensities and can readily be designed for intensities of several hundred roentgens per day. They can be made so the scale reading is reasonably linear with radiation intensity, and the sensitivity range can be altered by changing the size of the ion chamber or by changing the value of the series resistor. If the ion chamber and the electrometer tube are put into sealed units, there will be no sensitive insulation exposed to dust and moisture, and hence these instruments are quite reliable under adverse conditions.

Ion chambers can be used to detect α-particles if the chamber is equipped with a very thin window. An α-particle once inside the chamber may produce as many as 10^5 ion pairs over a very short path while a β-particle will produce only 10^3 ions in traversing the entire chamber. In a very thin chamber the beta ionization may be still further reduced without a corresponding reduction in the α-particle ionization. The pulse passed on to the amplifier will therefore be much greater for an α-particle. With this arrangement it is possible to detect α-particles in the presence of a considerable amount of beta and gamma radiation. If measurements of alpha activity are not desired, a thicker window is used which will exclude the α-particles. A still thicker window will exclude the β-particles as well, and only gamma radiation will be measured.

9.07 Geiger-Mueller Counters

Geiger-Mueller (G-M) counters take advantage of the gas amplification that can be obtained when high accelerating voltages are applied to an ionization chamber. Ion chambers are usually operated at atmospheric pressure or even under a positive pressure. Because of the small mean free path at these pressures excessive voltages are required to produce avalanche ionization, and G-M tubes

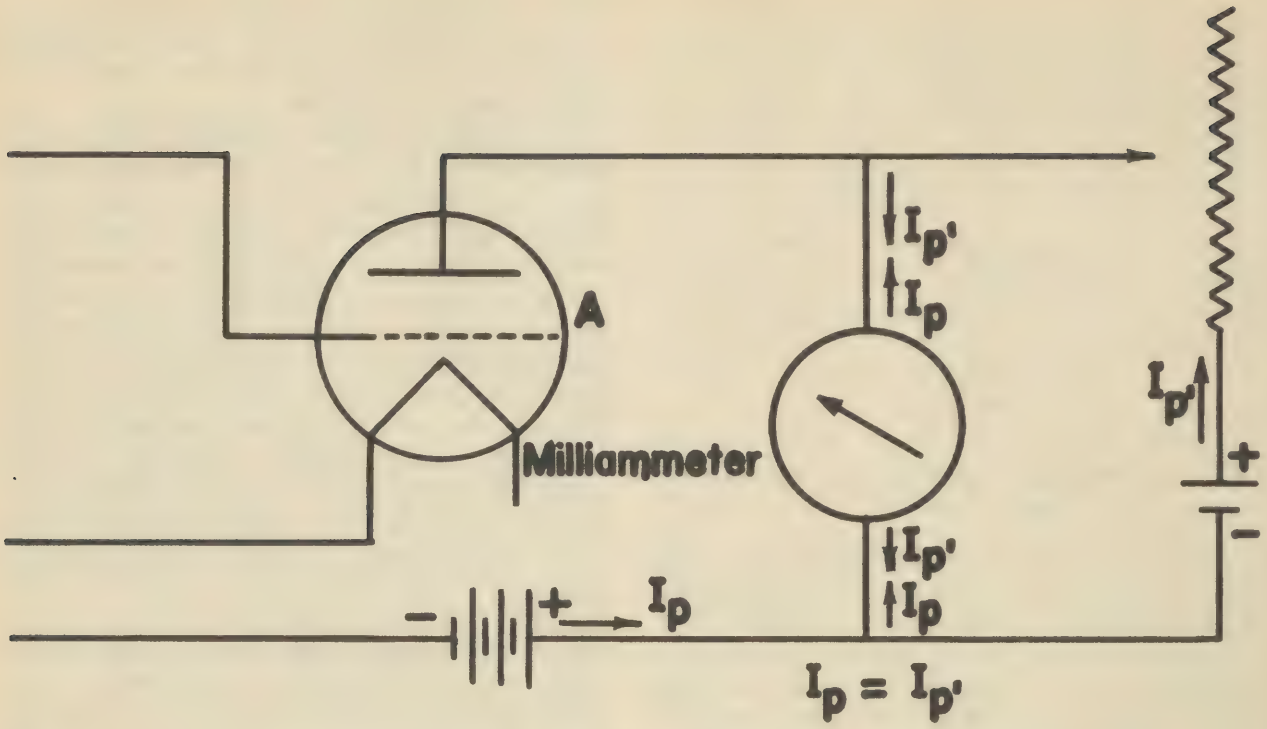


FIGURE 9–8.—Ion chamber with zero current bucking amplifier circuit.

are seldom operated at atmospheric pressure. If the pressure in an ionization chamber is reduced to about 10 centimeters of mercury, the mean free path will be increased, and gas amplification can be obtained at voltages of 250–1,500 volts depending on the gas and the tube dimensions.

Ion chambers are made in many shapes and sizes, but successful G-M counters usually have a cylindrical cathode from 1 to 10 centimeters in diameter with a length from 2 to 10 times the diameter. The anode consists typically of an insulated axial wire 0.001-inch to 0.005-inch in diameter. Future discussions will therefore be confined to cylindrical structures.

To simplify the discussion assume such an ionization chamber filled with gas to an absolute pressure of 10 centimeters of mercury and exposed to a constant amount of radiation, each ionizing particle or photon having the same energy. Each ionizing particle entering the chamber will produce a definite number of ion pairs in the gas, and these ions will proceed to the collecting electrodes where they will be neutralized and will produce a pulse of current in the external circuit. If there are a large number of pulses per second, they will appear on the meter as a steady current.

Assume for the moment that there are few pulses and that the size of each pulse can be measured. If now the size of the pulse is plotted against the voltage applied to the electrodes, a curve similar to that of figure 9–9 will be obtained. Regions *A* and *B* represent the normal ionization chamber working conditions where the only ions contributing to the pulse are those produced by the original radiation. Over region *C* there is some gas amplification occurring very close to the central wire. The electric field (volts per centimeter) is not uniform as is the case between two parallel plates, but increases near the central wire. Hence an ion near the central wire will receive a greater acceleration in one mean free path than will a similar ion near the outer cylinder. In this region the gaseous amplification is quite stable for any given voltage and does not depend on the number of initial ions present. Thus if the voltage is adjusted to a value such that the gas amplification factor is 10^3 and an incident β-particle produces 100 ion pairs, the pulse received at the

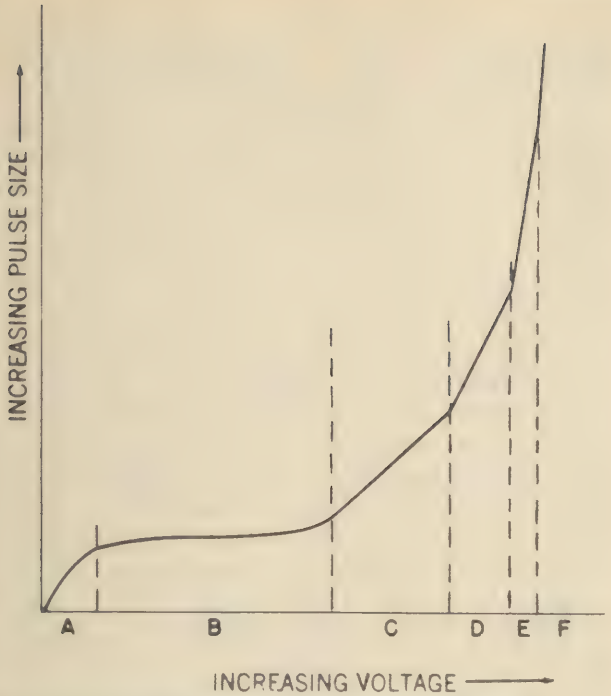


FIGURE 9–9.—Ion chamber pulse size versus voltage.

electrode will be $100 \times 10^3 = 10^5$ ions. Under the same voltage conditions an α-particle producing 10^5 primary ion pairs will yield a pulse of $10^5 \times 10^3 = 10^8$ ions. Because of the rather strict proportionality between the amounts of initial and total ionization this portion of the curve is known as the *region of proportionality*, and a counting tube operating in this region is called a *proportional counter*. As will be described later a proportional counter can be used to measure α-particles or neutrons in the presence of strong beta and gamma radiation. With typical designs the proportional region will extend to gas amplification factors of about 10^4.

If the voltage is raised still further, the gas amplification factor will continue to increase, but in region *D* the amplified pulses are no longer proportional to the number of primary ions. A sort of saturation effect begins to enter at this point and consequently a few primary ions will produce nearly as many total ions as are obtained from a large number of primaries. There is still some difference in final pulse sizes however, so this region is known as the region of limited proportionality.

The gas amplification continues to increase with further increases in voltage, and region *D* gradually changes to region *E* where all proportionality ceases. Here a single ion pair is sufficient to produce an amplified pulse of the same size as that obtained from a large number of primary ions. This is known as the *Geiger region* and is characterized by gas amplification factors of the order of 10^8. This is the portion of the tube characteristic commonly used for counting beta and gamma radiation.

Except in very special circumstances β-particles have a wide range of energies and consequently a wide range of ionizing power. In counting them, however, it is usually desirable to know the total number of particles with no discrimination against those of low energy. The Geiger region is ideally suited for this type of detection since here all ionizing events result in equal pulse sizes. The same situation exists for gamma radiation since this is detected through the ionization produced by electrons ejected from the walls of the tube by the gamma rays.

The Geiger region usually extends over a range of about 200 volts. When still higher voltages are used, the region of *continuous discharge*, *F*, is reached. In this region the tube is too unstable for useful operation, and care must always be taken to keep the tube voltages below the continuous discharge value. Actually the tube does not go into continuous discharge but rather produces a series of closely spaced pulses from one initial ionizing event. Although G-M tubes are never operated in the continuous discharge region, the mechanism producing this instability is important in the Geiger region also, and so warrants some discussion. Because the phenomena involved in the mechanism at the discharge of a G-M counter are extremely complicated, this discussion will be simplified and incomplete.

It has already been pointed out that avalanche ionization is most likely to take place in the vicinity of the central wire, since here the electric field is high and each electron, on its way to the central wire, can acquire enough energy for further ionization in each mean free path. Near the central wire therefore a large number of electrons and positive ions will be formed in the first avalanche. The electrons have a small mass and are already close to the central wire so they will move toward it with high velocities and will be completely collected by the wire in 10^{-6} seconds or less. The

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positive ions, on the other hand, have to travel out to the negatively charged cylinder. Since they have comparatively large masses, they move much slower than the electrons. The positive ion cloud will reach the cylinder in perhaps 10^{-3} seconds, long after the electrons have been collected at the wire.

As a positive ion approaches very close to the cylinder, it will pull an electron from the cylinder and become a neutral molecule. In general the electron will go into one of the upper energy levels so the molecule, although neutral, will be in an excited state (ch. 5, sec. 5.07). The molecule will, however, promptly return to the ground state and in so doing will radiate a characteristic series of spectral lines. Some of these lines will be in the ultra-violet region of the spectrum and consequently will have sufficient energy to liberate photoelectrons from the metal cylinder. With high tube voltages a single photoelectron will be sufficient to start a second avalanche and thus the entire process will be repeated over and over again.

A second type of characteristic curve is helpful in understanding the operation of ionization chambers, particularly in the Geiger region. For obtaining this curve assume the tube to be exposed to a constant radiation intensity but with the incident particles or photons having unequal energies. Pulses per second when plotted against the applied voltage yield a curve similar to figure 9–10.

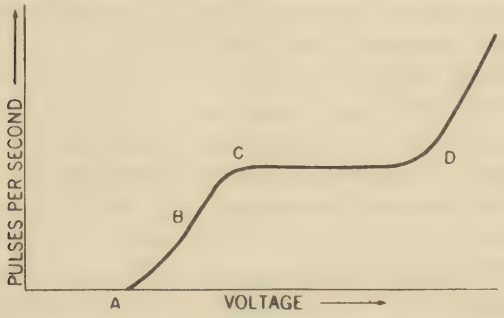

FIGURE 9–10.—G–M tube characteristic.

The associated electronic equipment for recording the number of pulses will not, in general, respond to the small pulses produced in the ionization chamber region where there is no gas amplification. Consequently the curve will have a threshold, A, below which no pulses will be recorded. As the voltage is raised and the gas amplification becomes appreciable, the most energetic particles will be counted, but the weak ones will be lost. This is the region of proportional counting AB. As the gas amplification continues to increase with voltage, more of the less energetic particles will be counted until point C is reached. C is the threshold of the Geiger region CD, and here practically every particle entering the tube is counted. D is the threshold of the continuous discharge region, which has no practical application.

The Geiger region CD is known as the *plateau*, and it is obviously desirable for a tube to have a long, flat plateau since here the counting rate does not depend strongly on the applied voltage. The plateau always has a slight upward slope, but it is quite possible to make tubes which show a change in counts of only 1 percent for a change of 100 volts. The length and slope of the plateau depend on several variables. To obtain desirable plateau characteristics the filling gas and pressure must be carefully chosen, and the central wire must be free from dust, sharp points or diemarks. Oxygen and water vapor are particularly undesirable and must be completely removed before filling.

It is evident from the above that if a G-M tube is to be used quantitatively, the voltage applied to it must be carefully adjusted to obtain the desired characteristics. Portable instruments are necessarily restricted to batteries for the high voltage supply, and this makes tubes operating on low voltages particularly desirable. With special filling gases the center of the plateau may occur at about 250 volts instead of the usual values of 800–1,200 volts.

Fixed laboratory instruments are usually operated from the power lines instead of from batteries and special regulating circuits are used to maintain constant voltage. For laboratory operation it is not necessary to have low voltages, and high-voltage, long-plateau tubes are usually used. The voltage setting for proper proportional counting is more critical than for operation in the Geiger region and thus proportional counters are essentially laboratory instruments.

9.08 The Counter Tube Gas.

Many gases, even though they do not have the optimum characteristics, are suitable for counter

operation. Argon is a very satisfactory gas and is used in practically all counters. There are, on the other hand, gases which are completely unsuitable. These are primarily those gases which tend to form negative ions instead of positive ions. If negative ions are formed by the addition of an electron to the neutral molecule, they will move toward the central wire as do the electrons but with the lower velocities characteristic of heavy ions. Consequently they will arrive at the wire long after the first avalanche has been produced by the electrons. When they near the wire, the extra electron may be removed by the intense field, and it will then proceed with a high velocity and start a second avalanche. The tendency to form negative ions makes oxygen, water vapor, and carbon dioxide completely unsuitable for use in counter tubes.

Counter tubes filled with any noble gas, such as argon, are said to be nonquenching or slow. In such tubes a single discharge will be self-perpetuating by the photoelectric effect at the cathode, even when the voltage is set at the center of the Geiger region. To eliminate this the counter may be operated with a series resistance, as indicated in figure 9–11. This is necessary in any case since the tube will usually be coupled to a voltage-actuated device. If the series resistance is made very large, say 10^9 ohms, there will be a substantial voltage drop across it even for a small pulse. With a pulse of 0.1 microampere, this voltage drop will be 100 volts. Then during the passage of the pulse the tube voltage will be decreased by 100 volts, and the resultant decrease in the gas amplification factor will be sufficient to prevent the second avalanche that might have been formed by the photoelectrons. When the discharge terminates, the current drops, the voltage rises to its original value, and the tube is ready to respond to a second ionizing event.

Unfortunately the series resistance must be made very large in order to obtain a sufficient voltage drop, and this results in a very slow counter. If fast operation with non-quenching counters is desired, special electronic quenching circuits must be used. They will be described later.

It is possible however, to construct counters in which the discharge can be stopped with small values of series resistance. These are known as *self-quenching* or fast counters. A self-quenching counter can be produced by adding to the usual filling gas a small amount of a polyatomic vapor, such as alcohol or xylene. These complex molecules strongly absorb ultra-violet light, and by this mechanism the photoelectric emission at the cathode is prevented. With self-quenching counters the series resistance may be reduced to 10^6 ohms or even lower.

Most of the polyatomic molecules introduced to make self-quenching counters are vapors at room temperature, and these counters are apt to show a sensitivity which changes with temperature. A further disadvantage lies in the fact that some of the quenching gas is broken down (dissociated) at each discharge, and so these counters have a limited life. Life does not mean deterioration with time but with use. A very satisfactory self-quenching counter can be made by filling the tube with 10 percent alcohol and 90 percent argon to a total pressure of 10 centimeters of mercury. In such a counter there may be 10^{20} molecules of alcohol. Perhaps 10^{10} molecules are dissociated at each discharge so the alcohol will be completely gone after 10^{10} discharges, and operation will be erratic even before this. The self-quenching feature usually outweighs this disadvantage, and self-quenching counters are widely used.

The α-particle efficiency of practically any counter is 100 percent, for any α-particle which enters is almost certain to end its flight within the tube and to produce massive ionization along its path.

With a gas such as argon, which has a high specific ionization, it is highly improbable that a β-particle can traverse a counter without producing enough ions to initiate the discharge. From this standpoint then the β-particle efficiency of a counter is very high and may be well over 99 percent. If the efficiency is considered as the ratio of the number of counts to the number of particles striking the counter tube, the efficiency will be somewhat less because some of the alphas and low energy betas will not penetrate the wall. This is not the usual definition of counter efficiency because it gives a figure which depends on the energy of the incident particles.

The efficiency of the ordinary counter for gamma radiation is very low, of the order of 1 percent or less. A γ-ray is detected only by the electrons which it produces in the counter walls or in the

gas, and if a γ-ray traverses the counter without producing either Compton electrons or photoelectrons or possibly electron pairs, it will not be detected. The probability of producing any of these electrons is low, and consequently a counter tube will respond to only a small fraction of the impinging γ-rays. The efficiency can be somewhat increased by making the cathodes of a heavy metal with a greater γ-ray absorption, but the improvement is not great.

Some G-M tubes are photosensitive, and this is usually an undesirable feature. If the cathode surface has a low photoelectric threshold, ultraviolet or even visible light may have sufficient energy to produce photoelectrons, and these will initiate the discharge. All G-M tubes should be tested for photosensitivity. This photosensitivity can be eliminated by coating the tube with an opaque material.

9.09 Neutron Counters

With the recent increase in interest in neutrons there has been a considerable development in counters for neutron detection. Any counter will give counts when placed in a neutron field, but better results can be obtained with specially designed tubes. To detect slow neutrons the counter is filled with boron trifluoride, BF_3, which is a gas at room temperature. A slow neutron may produce a nuclear reaction with the boron. This reaction liberates a considerable amount of energy, and the α-particle and the recoiling lithium will have sufficient kinetic energy to produce heavy ionization which will trip the counter. By using the counter in the proportional range it is possible to obtain a count for each disintegration even in the presence of large beta and gamma intensities. The capture probability decreases with the neutron velocity so the reaction is not efficient for fast neutrons.

Fast neutrons may be detected through the recoil atoms which they produce when they collide with the gas atoms in the counter. The recoil atoms produce intense ionization, and hence if the counter is adjusted to the proportional range, the counter will discriminate against beta and gamma radiation. Fast neutron counters have a rather low efficiency because of the low cross section for the collision process. Neutron counting is complicated by the change in behavior with velocity, and the present neutron counters are far from satisfactory.

9.10 Geiger Counter Circuits

Geiger counters are invariably operated with the central wire positive and with a resistance in series with the tube and the high voltage supply. The current pulse produced by an ionizing event in the tube will therefore produce a voltage pulse across this resistor. This pulse will be negative because before the discharge there was no current flowing and the wire was at full positive potential.

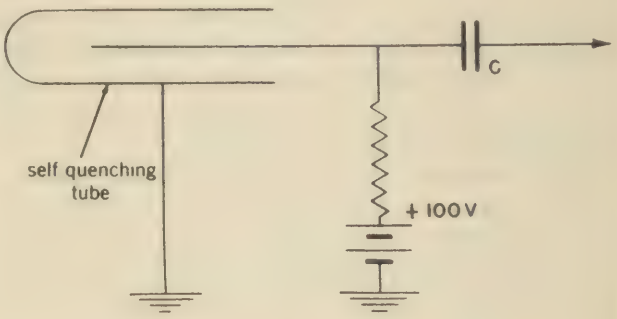

FIGURE 9–11.—G–M tube with a series resistance and a coupling condenser.

With self-quenching tubes condenser coupling, as shown in figure 9–11, is the simplest method for transmitting the impulse to the counting circuits. The pulse from a G-M tube is of short duration (perhaps 10^{-4} seconds) and hence is equivalent to a high frequency alternating voltage. Because of this the pulses are easily transmitted by small condensers of 50-100 micro-microfarads. The condenser must be well insulated since it is in a high voltage circuit, and any appreciable leakage current will disturb the low current counter circuit.

With a non-self-quenching tube an auxiliary circuit must be used to stop the discharge without the use of excessive values of series resistance. The Neher-Harper circuit (fig. 9–12) is one method for quenching the discharge. A tube with a sharp plate current cut-off, such as the 6C6 or 6J7, is most suitable for this circuit. The control grid is maintained at a point slightly beyond plate current cut-off by battery B_1, and the high voltage is applied to both the G-M tube and the quenching tube plate. With no pulse there is no current flow in either the G-M tube or the quenching tube.

When a pulse occurs in the G-M tube, there will be a current flow through both R_1 and R_2, the cylinder will become somewhat positive, and a positive pulse will be applied to the grid of the quenching tube. This tube will then draw a large plate current through the resistor R_2, and this will drop the potential of the central wire and extinguish the discharge. A negative pulse will be transmitted by the condenser to the following circuits.

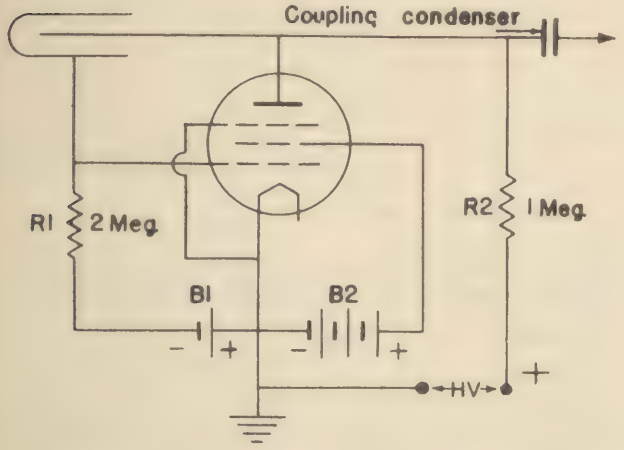

FIGURE 9–12.—Neher-Harper quenching circuit.

In the Neher-Pickering quenching circuit (fig. 9–13) the quenching tube is in series with the G-M tube and the resistance R_1. In the absence of a pulse there is no negative voltage on the quenching tube control grid, and saturation current is drawn. When a pulse trips the G-M tube, a large negative pulse appears on the grid of the quenching tube. This cuts off the plate current and removes the voltage from the G-M tube. With this quenching circuit the cylinder of the G-M tube can be maintained at ground potential which is a distinct advantage in many biological applications where the outside of the counter may be in contact with liquids or body tissue. The Neher-Pickering circuit, on the other hand, requires a separate voltage source for the filament of the quenching tube because the cathode is at a high positive potential. The quenching tube also puts a large, constant drain on the high voltage power supply. It willl be noted that a pulse of either polarity can be obtained from the Neher-Pickering circuit.

A third useful quenching circuit is the multivibrator arrangement shown in figure 9–14. One tube will be biased nearly to cut-off with battery B_1, while the other will have zero bias, as shown. Such a circuit will have one stable position with T_1 drawing maximum current and T_2 cut off. When a negative pulse from the G-M tube is impressed on the grid of T_1, the plate current is reduced, and an amplified positive pulse appears in the plate circuit. This is impressed on the grid of T_2 through C_3 and results in a current flow in tube T_2. The plate drops in potential, and this amplified negative pulse is fed back to the grid of T_1 through C_2. This reinforces the original negative pulse, and the process continues until T_2 is taking maximum plate current and T_1 is cut off. As soon as the plate current stops changing (when T_1 nears cut-off and T_2 nears saturation), the condensers C_2 and C_3 will begin to discharge, and the circuit will return to its original state. When this happens a large negative pulse will appear at the grid of T_1, and when this is transmitted to the G-M tube through C_1, the discharge will be quenched. Each pulse from the counter tube will therefore send the circuit through one cycle of operation.

Because of the regenerative action large voltage swings can be attained, and by a proper choice of T_2 substantial amounts of power are available for operating recording instruments. If a tube such as a 6V6 or 6L6 is used as T_2, a mechanical counter can be put directly in the plate circuit to count the pulses. With a smaller tube for T_2 a direct current milliammeter can be put in the plate circuit for reading the average number of pulses, and a pair of phones may be used for counting individual pulses at low radiation intensities. This circuit is therefore well adapted for portable instruments.

The time required for the multivibrator circuit to complete one cycle of operation depends on all circuit constants, but is strongly dependent on the values of C_2 and C_3. This fact permits a very simple method of changing the sensitivity range when the circuit is used in a portable instrument with a direct current milliammeter in the plate circuit of T_2. It will be remembered that a direct current meter reads average values, and so the reading of such a meter placed in the T_2 plate circuit will depend not only on the number of pulses but also on the length of each pulse. This

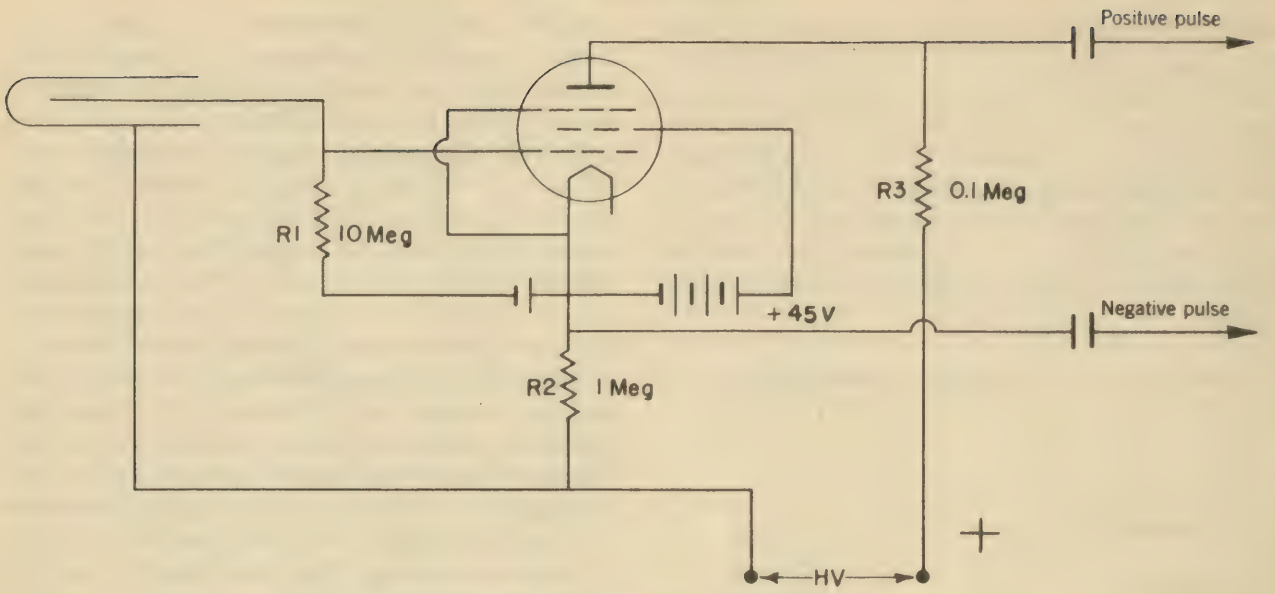

FIGURE 9–13.—Neher-Pickering quenching circuit.

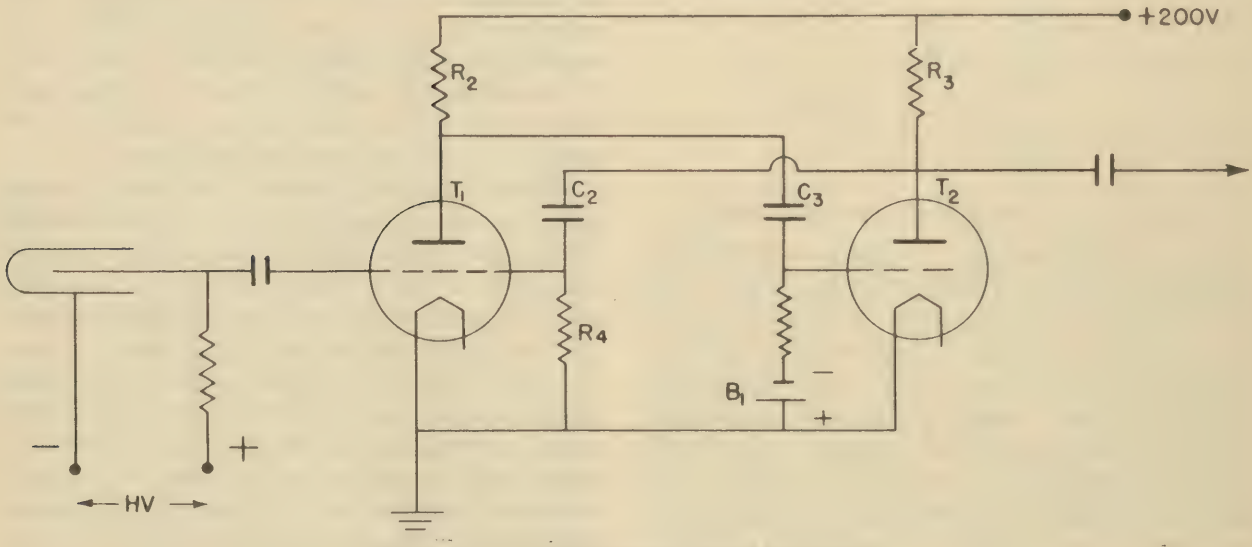

FIGURE 9–14.—Multivibrator quenching circuit.

is illustrated in figure 9–15 for evenly spaced pulses. The same situation will obtain with the random spaced pulses produced by a G-M tube in a radiation field.

When the instrument is in a weak radiation field and only a few pulses per second are being recorded, a large value of C_2 can be selected by a switch, and the few broad pulses will produce a substantial average current which can be read on the meter. With high-intensity fields the meter will read off-scale, but by changing to a smaller value of C_2 each pulse can be shortened and a lower average current obtained. It is necessary, of course, to have a separate calibration for each value of C_2. It should be pointed out that the average current read by the meter depends also on the height of the pulses. With constant battery voltages this is no problem, as the tubes swing from cut-off to saturation, but the height will decrease with battery voltage and result in a reading that is too low. It is evident that with a mechanical recorder the above circuit will record the total number of counts from the G-M tube. With an averaging meter in the circuit the instru-

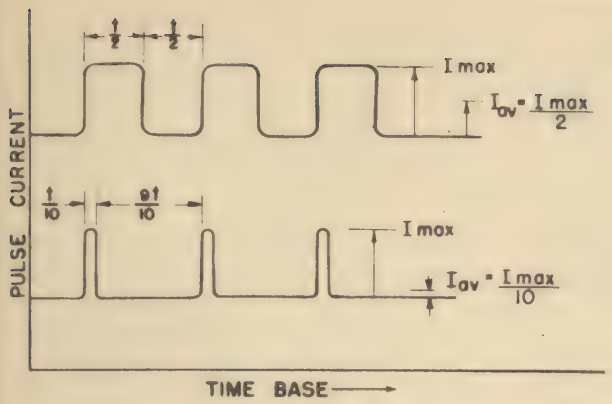

FIGURE 9–15.—Pulse shapes.

ment becomes a *rate meter* which will measure the intensity of radiation.

9.11 Scaling circuits

If a mechanical counter is connected directly in the multivibrator circuit, the possibilities for fast counting inherent in the G-M tube cannot be realized. A G-M tube can produce a pulse, be quenched, and be ready to receive a second pulse in perhaps 2×10^{-4} seconds and hence should respond to 5,000 equally spaced counts per second. The associated electronic circuits can be made equally fast so in a simple direct counting circuit the limit on speed is set by the mechanical register. These can be made to count perhaps 100 times per second, but this is an upper limit, and it is more satisfactory if they do not receive over 50 impulses per second. To fully utilize the capabilities of the G-M tube it is desirable to scale down the number of pulses so the mechanical counter will have to respond to only a known fraction of the total. The electronic arrangements for doing this are known as *scaling circuits*.

Scaling circuits are based on a two-tube basic circuit which divides the number of pulses by two and is known as a scale of two. There are many circuits capable of doing this, and it is not possible to discuss them in detail here. A typical scale-of-two circuit is shown in figure 9–16. This circuit is somewhat similar to that of the multivibrator but is completely symmetrical and has two stable positions instead of one. Because of the cross-coupling condensers C_2 the circuit will be in equilibrium when either tube is cut off and the other is at maximum plate current.

When a negative pulse comes in from the G-M tube or quenching circuit, it will have no effect on the tube that is already cut off, but it will reduce the plate current of the other tube of the pair and produce an amplified positive pulse in the plate circuit. This amplified positive pulse is applied to the grid of the cut-off tube through the cross-coupling condenser, and current will flow in this tube. The net result of a single pulse then is to reverse the roles of the two tubes. The tubes will remain in the reversed position until the arrival of a second pulse which will restore the circuit to its original state.

The amplifier tube T_3, is biased to cut-off so that negative pulses on its grid will have no effect on the plate current. A positive pulse will produce a plate current pulse, and a negative signal will be transmitted through C_4.

It is evident then that this circuit will transmit every second pulse, and by constructing a series of such circuits the incoming pulses can be reduced by a factor of 2, 4, 8, 16, 32, 64, etc. The most common scaling circuits are usually scales of 32 or 64. It is customary to insert neon indicator lamps in one side of each stage. This serves two purposes. By observing them it is possible to determine whether the instrument is scaling properly. They are also used as interpolation indicators to record counts less than the total number required to record once on the mechanical counter. As a simple example assume the circuit of figure 9–16 used as a scale-of-two with the mechanical counter in the output of T_3. The counter will record one for every two pulses but will take no account of the odd pulses. At each odd pulse the neon lamp T_4 will be lighted so this can be used to keep track of the odd pulses. In an extended scaling circuit the lamps are given values of 1, 2, 4, 8, 16, etc. The sum of the values of all the lamps that are lighted when the counter is stopped is the total number of pulses not counted by the mechanical recorder.

The mechanical counters are invariably magnetically actuated with a ratchet and pawl mechanism for transferring the pulses to a suitable scale indicator. The moving parts are made as light as possible to obtain a high response speed and to avoid excessive driving power requirements.

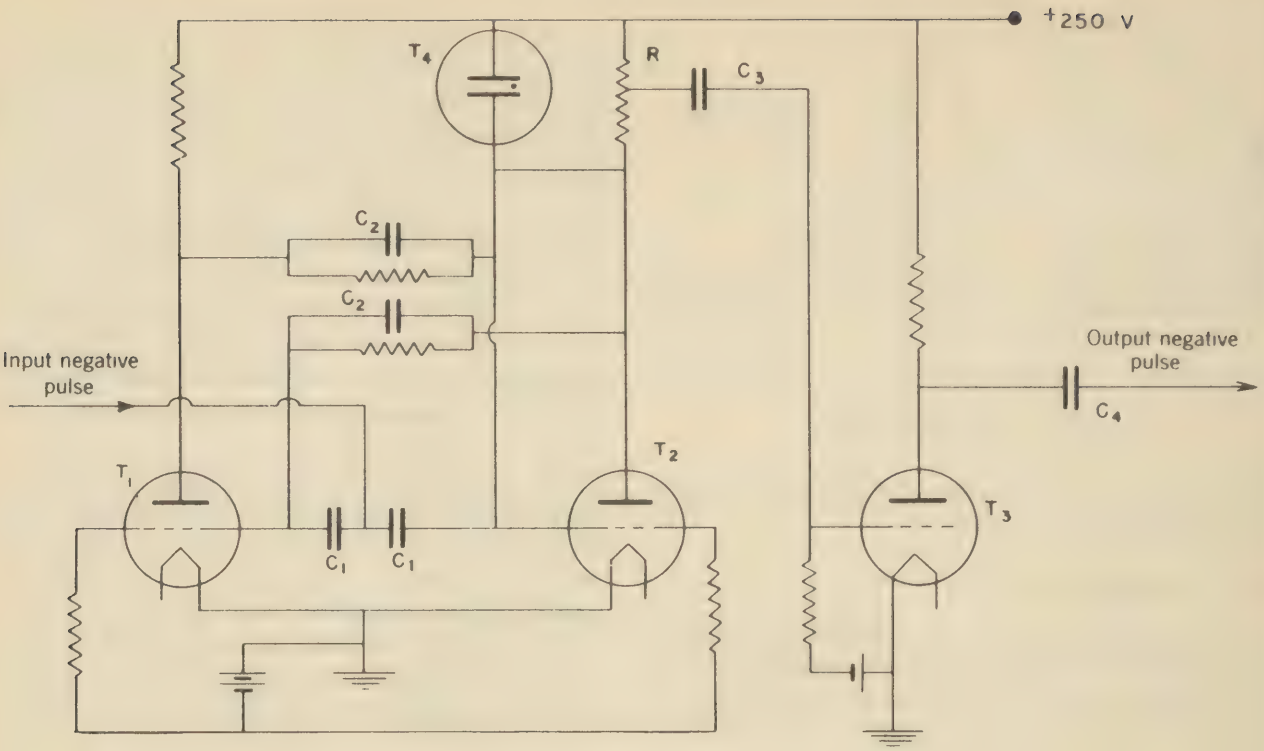

FIGURE 9–16.—G–M counter scaling circuit.

9.12 Calibrations and Standards

The instruments that have been described can be used to measure accurately ionization currents or the amount of ionizing radiation that enters a G–M tube, but it should be pointed out that none of these devices give an absolute measure of radiation intensities. It is therefore necessary to calibrate them in terms of known standards. This is not difficult if a γ-ray calibration is required in terms of roentgens. It has been established by careful measurements that 1 milligram of radium, in equilibrium with its products and enclosed in 0.5 millimeters of platinum or its equivalent, will produce an intensity of 8.4 roentgens per hour at a distance of 1 centimeter. If the radium is in a small container, the inverse square law can be used to calculate the intensities at other distances. The radium must be in equilibrium with its products to insure a constant amount of radon and all of the lower members of the disintegration series. The filter of 0.5 mm. of platinum is sufficient to stop all alpha and practically all beta particles and thus leave a pure gamma radiation. Standard γ-ray sources, properly aged and carefully calibrated, are available from the National Bureau of Standards.

If X-ray measurements are desired, it is preferable to calibrate at the energies which are to be measured. Even though thimble chambers are carefully designed they may show variations in response with changes in energy. G-M tubes are worse because the efficiency of the photoelectric and Compton effect changes considerably with energy. Calibration of X-ray measuring instruments should be carried out against primary standard ionization chambers or carefully calibrated secondary standards by a well-equipped laboratory such as National Bureau of Standards or by a reliable instrument manufacturer.

In making α- and β- particle measurements quite different considerations enter. Practically all α-particles are emitted with a few discrete energies, and all particles which enter an ionization chamber or G-M tube will produce a response. The problem then is to get a window thin enough to admit all of the particles or to introduce the active material directly into the chamber. Even when this is done the problem of chamber geometry

must be faced. Radioactive materials emit particles in all directions with equal probability and in general a chamber or G-M tube will intercept only a fraction of the total emission. For example, if the active material is spread in a thin layer on the bottom of the chamber, only one-half of the ejected particles will reach the gas and produce ionization. The remainder will strike the container and be lost. In general the geometrical arrangement is such that it is not possible to calculate the fraction of the particles intercepted by the sensitive volume of the chamber. It is then necessary to calibrate the chamber in terms of a known radioactive material. Various members of the naturally radioactive series are useful for this purpose. The disintegration constants for nearly all members of this series are well known, and it is possible to calculate the number of disintegrations per second expected from a known weight of the material.

In calibrating an instrument for β-particles the same general procedure is followed, but the energy range of the particles introduces a complicating factor. Most β-particles are detected by allowing them to pass through the thin wall of a G-M tube or ion chamber. Since the β-particles have all energies from zero to a maximum value, some of the low energy particles are bound to be lost in the window, and the fraction lost will depend on the maximum energy. In making β-particle calibrations, therefore, it is desirable to choose as a standard source an element which has about the same β-particle energies as the unknown. This is not always possible and so it is sometimes necessary to make corrections for differences in energy. Methods for β-particle calibration are not entirely satisfactory at present, and better sources are sorely needed.

Mention should be made of the behavior of thin wall G-M counters used as survey meters in extensive areas contaminated with β- and γ-emitters. These instruments have been calibrated in terms of the roentgen, which is a unit applicable only to electromagnetic radiation. If the tube is directly exposed to beta radiation, as by opening a protective window, the instrument will respond to β-particles, and in general this reading will be several times the γ-ray reading obtained when the window is closed. It must be kept in mind that the β-particle reading bears no relation to roentgens and cannot be converted into these units. It is permissible to refer to the reading as roentgens equivalent, as is sometimes done, although even this is misleading, for the reading is a roentgen equivalent only as far as the meter is concerned. Such readings are useful for comparison purposes, but must be interpreted with caution.

9.13 Correction of Measurements

(*a*) *Statistical deviations.*—When radiation measurements are made, it is soon observed that all readings show fluctuations. This is not always due to the instability of the measuring instrument but is inherent in the radiation source. Nuclear disintegrations are completely random and independent processes. Thus whether or not a given nucleus disintegrates at a particular time does not depend on the state of any other nuclei. Such a process will obey the laws of statistics, and these laws predict that even though there is a definite average rate of disintegration, the number of disintegrations actually counted in a given time will show deviations from this average.

If a total of N particles are counted in any time interval it can be shown that the expected deviation D from the true value is given by

$$D=\sqrt{N} \tag{3}$$

The probable error $P.\ E.$ is defined as $0.67D$, so

$$P.\ E.=0.67\sqrt{N} \tag{4}$$

If a total count of 10,000 is made, the most probable deviation will be: $D=\sqrt{10{,}000}=100$ and the probable error will be 67 counts. It is usually more instructive to calculate the relative deviation or relative probable error, which is merely the deviation or error expressed as a fraction of N. Thus:

$$\text{relative deviation}=\frac{D}{N}=\frac{\sqrt{N}}{N}=\frac{1}{\sqrt{N}} \tag{5}$$

and

$$\text{relative probable error}=\frac{0.67}{\sqrt{N}} \tag{6}$$

In the above example the relative deviation will be $\frac{1}{\sqrt{10{,}000}}=0.01$ or 1 percent, and the relative probable error will be 0.67 percent. With these expressions it is possible to calculate the total num-

ber of counts that must be made to obtain a desired accuracy.

If counts are made on weak samples, the above considerations have to be modified because of the background count. It is found that all instruments show a small reading even when no radioactive material is brought near. This residual count or background, is due to cosmic rays, to radioactive materials in the earth, and to a slight radioactive contamination in the materials of which the instruments are made. The background is somewhat variable with geographical location but is fairly constant at a given place. The background also depends, of course, on the size of the chamber or counter tube. As a rough approximation a G-M counter in an uncontaminated area will have a background count of about 1 per minute per square centimeter of cathode area.

For an accurate count on a radioactive sample it is necessary to determine the background and subtract this from the count obtained when the sample is in position. The accuracy of the final result depends then on the accuracy of the two counts which are subtracted. Statistical theory shows that the deviation in the final result will be

$$D=\sqrt{D_1^2+D_2^2} \tag{7}$$

where D_1 is the deviation of the count of background plus radiation, and D_2 is the deviation of the background count. Since $D_1=\sqrt{N_1}$ from Eq. (3) then:

$$D=\sqrt{N_1+N_2} \tag{8}$$

As an example of the use of these relations assume a measurement made with zero background to have a relative standard deviation of 1 percent. Then $D=0.01=\frac{1}{\sqrt{N}}$ whence $N=10{,}000$ counts. Now suppose the same accuracy is desired when the background is equal to the activity. Then the count of background plus sample N_1 will be twice the background alone N_2, or $N_1=2N_2$. Then:

$$\text{relative deviation}=\frac{D}{N_1-N_2}=\frac{\sqrt{N_1+N_2}}{N_1-N_2}=0.01$$

or

$$=\frac{\sqrt{3N_2}}{N_2}=0.01$$

or

$$=\frac{\sqrt{3}}{\sqrt{N_2}}=0.01$$

Therefore

$$N_2=30{,}000 \text{ and } N_1=60{,}000.$$

Thus because of the presence of the background, nine times as many counts must be made to achieve the same accuracy and this will require six times the original counting time.

In general any sample whose activity is less than background is scarcely worth counting. (In this case the count with the sample in position will be less than twice that with the sample removed.) This shows the necessity for keeping the background as low as possible by avoiding all possible contamination of laboratory or instruments. Particular care must be taken when measuring liquids, either with immersion or jacketed counters. A background count should be taken before each count to be sure that no residual activity is left from previous samples. The exact methods for removing contamination depend on the nature of the contaminant and the structure of the measuring equipment.

(*b*) *Counter dead time.*—Another factor which affects the results of G-M tube measurements is the *counter dead time.* It has been pointed out that a G-M tube requires a definite time to neutralize the positive ions from one pulse and be ready for the next. This time is of the order 2×10^{-4} seconds, and so the tube should respond accurately to $\frac{1}{2\times10^{-4}}=5{,}000$ evenly spaced counts per second. But if a radioactive material is ejecting an average of 5,000 particles per second into the tube, many counts will be missed because many of the particles will be less than 2×10^{-4} seconds apart. This is another effect of the random nature of nuclear disintegrations. Even though the average rate is well below the limit of the counter, a few pulses will be too closely spaced and will be missed. It can be shown that if T_D, the dead time of the counter, is small compared to the average time between pulses, $\overline{T}$, then the relative error due to counter dead time will be

$$\text{relative error}=\frac{T_D}{\overline{T}} \tag{9}$$

As an example consider a counter with a dead time of 2×10^{-4} seconds counting 1,000 times a second. Then $\overline{T}=1/1000=10^{-3}$ seconds and the relative error $=\frac{2\times10^{-4}}{10^{-3}}=0.2$, or 20 percent. At this average rate therefore the counter will be missing 20 percent of the counts because of dead time. It will be noted that the error increases with counting rate, and hence high speed counting should be avoided if a high accuracy is desired. It will be evident that this particular error does not enter into ionization chamber measurements because an ion chamber will respond to simultaneous ionizing events.

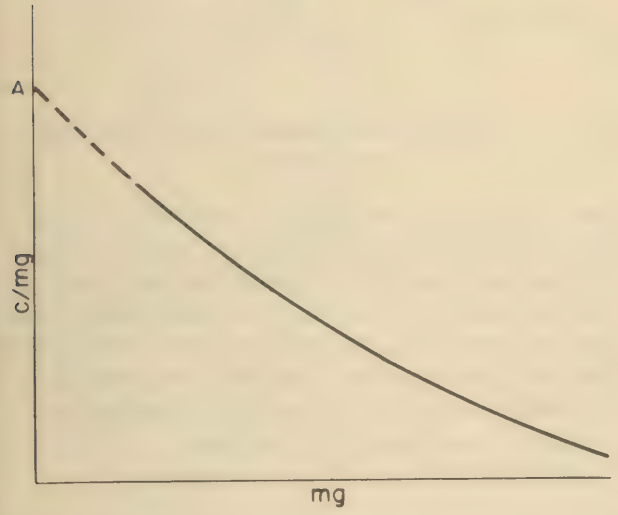

FIGURE 9–17.—Self-absorption curve with extrapolated value for zero absorption.

(*c*) *Self-absorption.*—In measuring the beta activity of solid and liquid samples it is usually necessary to correct for the self-absorption of the particles by the sample itself. This is particularly true if the maximum beta particle energies are low, as for C^{14} with 0.14 Mev particles or S^{35} with 0.11 Mev particles. In any case, ejected β- particles will have energies ranging from zero to a definite maximum value and the low energy particles will be stopped by relatively thin layers of material and will not reach the sensitive volume of the counter.

To correct for this a series of counts is made with a series of weighed samples. From these data a plot can be made of counts per milligram of material against the milligrams in the sample (fig. 9–17). The curve can be extrapolated back to zero milligrams, and the intercept on the counts per milligram axis will give the value that would have been obtained with no self-absorption. This curve can then be used to correct all weighed samples to zero thickness if the materials being measured have comparable densities.

9.14 Decay Curve Measurements

In all of the previous discussions it has been assumed that a single measurement would be made on a given radioactive sample. In most cases this gives sufficient information, but occasionally it is desirable to make a series of measurements to determine the decay curve of the active components. This is a useful method of analysis since it is usually possible to identify a radioactive material if its half-life is known.

In determining decay curves care must be taken to locate the sample in the same geometrical position at each measurement. If possible the sample should be left in position between measurements. If a series of counts are taken and the logarithm of each count is plotted against the time at which it was taken, a straight line of slope λ will be obtained.

If there are two radioactive substances in the sample, each will have a characteristic value of λ, and a simple linear relation will no longer be obtained. Figure 9–18 shows the results with two

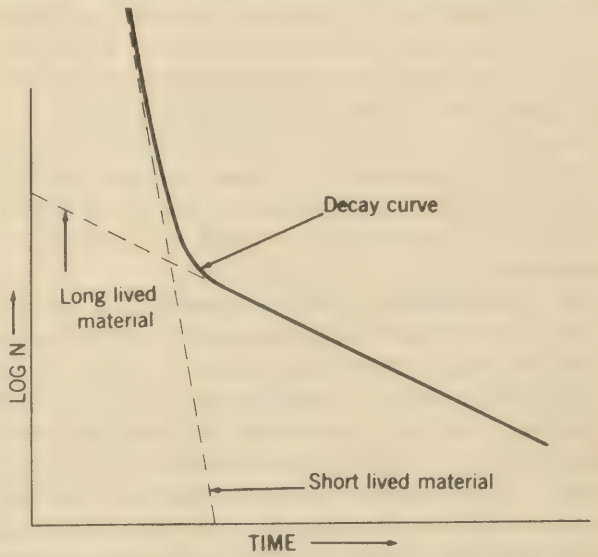

FIGURE 9–18.—Semilogarithmic plot of the decay of a short and long lived isotope.

Note.—The separation of two half-lives from a composite decay curve. (*N* is the number of counts per minute with the sample in constant orientation.)

half-lives present. If the plot is continued long enough the short-lived element will decay to a point where it no longer makes an appreciable contribution, and the curve will become linear. The straight portion of the curve can be extrapolated back to zero time, and this line will represent the activity due to the long-lived component. If a series of values along this curve are subtracted from the corresponding values on the experimental curve, the remainders will be the activity due to the short-lived component. If these values are plotted logarithmically, a straight line will be obtained having a slope equal to the short-lived decay constant.

9.15 Photographic Dosimetry

Photographic materials are also important tools for the measurement of radiation since high speed particles and high energy photons produce developable images. It was, in fact, the effects of penetrating radiations on photographic plates that led Becquerel and the Curies into the research that has developed into the present field of nuclear physics.

Although photographic films and papers lack the accuracy attainable in the laboratory by electrical methods, they still play an important role in radiation measurements. A film is one of the simplest detectors of radiation, is small and light, can be obtained with a wide range of sensitivity, provides a permanent record of exposure, and has no complicated electronic circuits to get out of adjustment. For many applications these facts more than outweigh the disadvantages of film processing, the time required to obtain a measurement, and the variations inherent in photographic materials.

A photographic emulsion consists of a thin ayer of a silver halide and gelatin spread on a base of glass, cellulose, or paper. When visible light strikes such an emulsion, some of the silver halide is rendered developable by suitable chemicals into a deposit of metallic silver. The interaction of light with the silver halide is not well understood, but some sort of ionization process is undoubtedly involved. After an emulsion has been exposed to radiation, there is no visible sign of any change, but a latent image exists which can be made visible by development. In the developing solution the latent image is converted into a black deposit of metallic silver. The amount of blackening is a function of the amount of exposure and the conditions of development.

The blackness of the processed film or plate is usually measured with some sort of a densitometer, figure 9–19. A strong light source is focussed to a small image and allowed to fall on a photocell which is connected to a meter. When the light falls directly on the cell, a meter reading will be obtained which is proportional to the light intensity I_0. When the film is put in the light path, some of the light will be absorbed by the developed silver, and a lower reading corresponding to an intensity I will result. The ratio of these intensities is called the *opacity*, O.

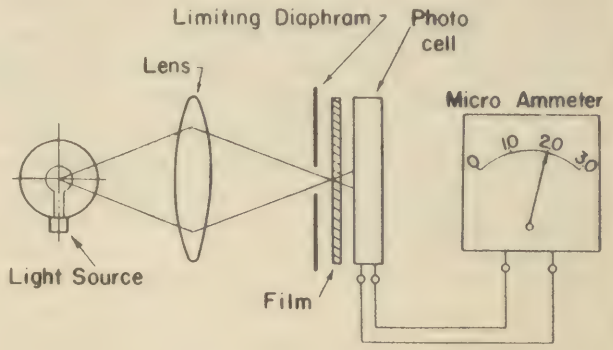

FIGURE 9–19.—Schematic arrangement of densitometer with photocell.

$$\text{Opacity} = \frac{I_0}{I} \tag{10}$$

The inverse ratio is the *transmission*, T.

$$T = \frac{I}{I_0} \tag{11}$$

A more useful measure of film blackening is *optical density*, D, defined by:

$$D = \log_{10} \text{Opacity} = \log_{10} \frac{I_0}{I} \tag{12}$$

When density measurements are made, the values obtained depend to some extent on the type of optical system used in the densitometer. The silver deposit scatters light as well as absorbs it, and hence the reading depends upon how much of this scattered light reaches the photocell. In some of the simpler densitometers there is no

focused beam, all measurements being made with diffused light. It is preferable to use instruments with sharply focused light beams. In any case a particular set of density measurements should be made on the same type of densitometer to avoid variations due to changes in scattering.

If the density is plotted against $\log_{10}$ (exposure), the characteristic curve of the emulsion is obtained (fig. 9–20). The characteristic curve consists typically of three portions; the toe *AB*, the linear portion *BC*, and the shoulder *CD*. Obviously one emulsion can respond to only a limited range of exposures. For greatest accuracy only the linear portion should be used because there is the greatest change of density with exposure in this region. If a different exposure range is desired, a different emulsion can be used. Figure 9–21 shows the characteristic curves of two emulsions which have proved useful in monitoring radiation hazards. Table I lists a series of emulsions that have proved useful for measuring beta and gamma radiation.

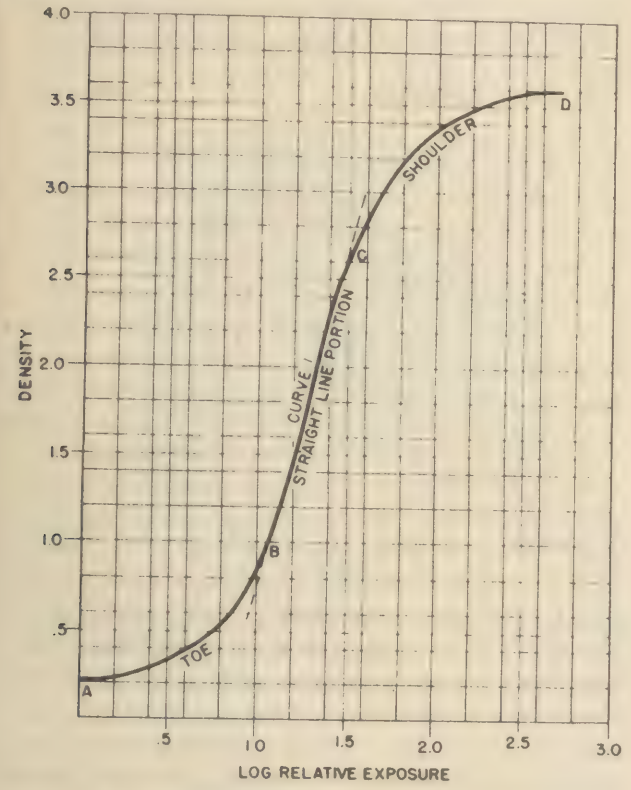

FIGURE 9–20.—Characteristic curve of a photographic emulsion.

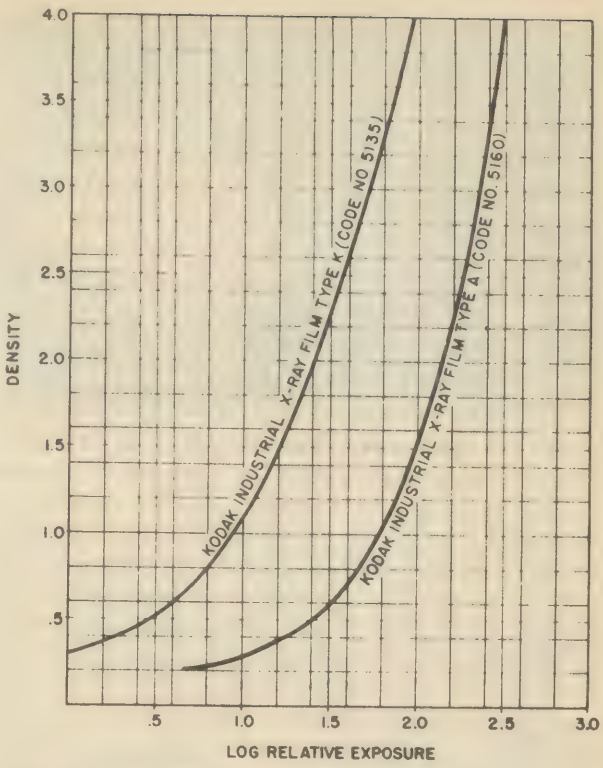

FIGURE 9–21.—Characteristic curves for Types K and A emulsions.

TABLE I

Emulsion:	*Useful sensitivity range (roentgens)*
Type K	0. 05–2. 0
Type A	1. 0–10
Cine positive 5301	5–80
Cine positive fine grain 5302	40–400
Kodalith 6567	70–700
Kodabromide G–3	400–8, 000
548–0, double coat	2, 000–10, 000
548–0, single coat	5, 000–20, 000

It can be seen from table I that a single emulsion will cover an exposure range of about 1–10. One emulsion on paper is included because it is the only product having that particular sensitivity range. Density measurements on paper are made by reflected light and in general are more difficult and less satisfactory than density measurements made by transmission. Fortunately there is little use for emulsions in the high ranges, and the low exposures are adequately covered by transparent materials.

Photographic film meters are usually made into packets of dental film size (1¼ × 1¾ inches) and covered with an opaque wrapping to protect the

film from visible light. Any combination of suitable emulsions can be put into a single packet. A cross of thin sheet lead about 1 mm thick is customarily attached to the packet. This absorber is sufficient to stop all β-particles so any darkening under the cross will be due to γ-rays. The cross also serves to enhance the darkening due to γ-rays because of the larger number of electrons ejected from the lead. The regular wrapping is sufficiently thin to permit the penetration of all but low energy β-particles. Thus the film can be used to measure both beta and gamma exposures.

In determining the characteristic curve of emulsions the assumption was made that all processing procedures were uniform. This is a very important restriction because the film density depends on processing methods, particularly on the development time and temperature. The slope of the characteristic curve is known as the gamma (this has no relation to γ-rays) of the emulsion. Figure 9–22 shows the effect of development time on

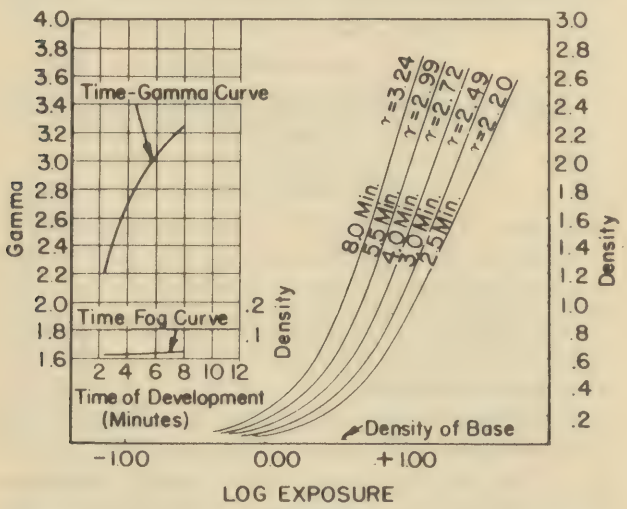

FIGURE 9–22.—Effects of developing time on gamma and density.

density and gamma. Since the speed of development increases with temperature, similar effects will be observed if the developer temperature is changed. Furthermore, there is always some blackening due to the direct action of the chemicals on the emulsion, and this chemical fog must also be controlled.

In general, film processing is carried out in accordance with the manufacturers' recommendations, but variations may be used satisfactorily. Whatever procedure is used, it is most important to control time and temperature as accurately as possible. The developer should be in a tank surrounded by a constant temperature bath, and the films agitated throughout development. Fixing and washing baths need not be temperature controlled, but temperatures above 75° F. should be avoided to prevent frilling of the emulsion from the base. The importance of time and temperature control, scrupulous darkroom technique, and the use of fresh chemicals cannot be overemphasized

9.16 Film Calibration

Films are not absolute measures of radiation and must be calibrated with sources of known strength. For a γ-ray calibration, radium gives a convenient source whose γ-ray field is well known in terms of the milligrams of radium. For β-particle calibration, uranium metal is frequently used. This has a weak γ-ray component, and the α-particles cannot penetrate the film wrapping so any blackening will be due entirely to β-particles.

Photographic materials are not exactly reproducible in spite of great care in manufacture so it is necessary to calibrate at least one film from each batch. Actually films in a single batch may show some variation, but there is no way of calibrating each film, and variations of perhaps 20 percent in sensitivity may be expected with the best possible processing and calibration procedures. Processing techniques for calibration should be identical with those used to measure unknown radiation.

It must be remembered that films are always sensitive to radiation, and hence great care must be taken to prevent exposure before issue. This may be difficult when operating in a large contaminated area. Whenever it is suspected that unissued films have been exposed, a blank film should be processed and a new calibration run.

9.17 Alpha Particle Emulsions

Special emulsions are now commercially available which are almost insensitive to visible light, beta and gamma radiations, but which will respond to heavy particles such as protons, deuterons, or alpha particles. These particles have such a low penetrating power that the emitting substance must be placed in direct contact with the emulsion. These emulsions are not used for personnel monitoring but rather to detect α-particle

contamination. These emulsions will detect α-particles in the presence of strong beta and gamma radiation, and under conditions that make the operation of electrical α-particles detectors uncertain if not impossible.

With weak exposures the plate will not be uniformly darkened and individual α-particle tracks can be seen in a microscope. Since α-particles are emitted with an energy characteristic of the emitting nucleus, the track lengths may frequently be used to identify the alpha emitter. Figure 9–23 shows typical α-particle tracks from polonium.

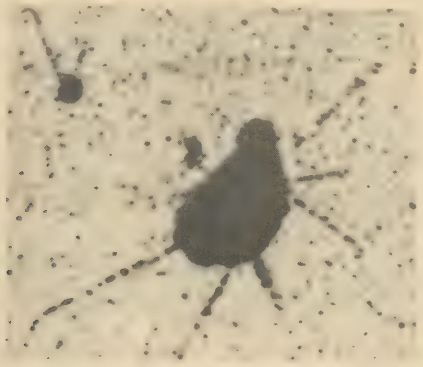

FIGURE 9–23.—Alpha particle tracks on a photographic emulsion.

If the α-particle contamination is low, exposures of several days may be required to obtain sufficient tracks for counting. In some cases this delay in obtaining information may be serious. It must be remembered, however, that the alpha emitters commonly encountered in radiological safety operations have long half lives and in some cases a delay in measuring the alpha activity may not be important.

9.18 Radio-autographs

The various film emulsions can be used to make radio-autographs of specimens containing radioactive materials. In figure 9–24 is shown the radio-autograph of a fish caught on the Bikini reef following the underwater detonation. Such a photograph reveals the distribution of radioactive material within the sample. By exposing sections of the specimen it is possible to determine the cross-sectional distribution as well. However it must be emphasized that the resolving power of photographic emulsions for determining the precise position is limited, and it is scarcely possible to determine the location of radioactivity to less than 1/100 mm.

FIGURE 9–24.—Radio-autograph of a surgeon fish caught on the reef between Bikini and Amen Islands.

To obtain such radio-autographs the sample is placed in direct contact with the film in a darkened room or container. The time of exposure may vary from a few seconds to several days or weeks. The radioactive material may be detected by the darkening of the negative or by light areas in the positive. By suitable selection of exposure time it is possible to investigate a wide range of intensities and detect extremely small amounts of radioactivity. By observing the film with a microscope and noting the different types of tracks it is frequently possible to determine the nature of the radioactive material in the sample.

9.19 Conclusion

While the authors have attempted to present both a comprehensive and a consistent picture of nuclear physics as related to this manual, it should be pointed out that the discussion has been of an elementary and semiquantitative nature. Certain fundamental properties of elementary particles, namely their statistics, spins, and magnetic moments, have not even been mentioned. Furthermore no attempt has been made to introduce wave mechanics other than as a crude explanation for alpha-emission. Many of the topics which have been treated here in a sentence or two are found well developed in the science of physics. Furthermore, many topics have been greatly simplified in this manual either by omission of detail or by modification of this detail.

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Appendix I

TABLE I.—*Table of fission products: characteristics*

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
30	Zn 72	49h	β^-, γ	1.5×10^{-5}	0.3 (~95%), ~1.6 (~5%)	γ
	Zn 73	<2m	β^-	----------	----------	----------
31	Ga 71	stable				
	Ga 72	14.25h	β^-, γ	----------	0.8 (~65%), ~3.1 (~35%)	0.64 (~10%), 0.84 (~45%), 2.25 (~45%)
		14.1h			1.71	1.17, 2.65, 2.1
	Ga 73	5h	β^-	1.0×10^{-4}	1.4	no γ
32	Ge 72	stable				
	Ge 73	stable				
	Ge 74	stable				
	Ge 75	89m	β^-, γ	----------	1.2, 1.1	γ
	Ge 76	stable				
	Ge 77	12h	β^-, γ	0.0037	2.0	γ
		11h			1.9	
	Ge (78)	2.1h	β^-, γ	0.020	~0.9	γ
33	As 75	stable				
	As 77	40h		0.0091	0.7	----------
	As 78	80m	β^-, γ	----------	1.4	0.27
		65m				
	As (78)	90m	β^-	0.020	1.4 (70%), 4.1 (30%)	----------
	As 81	<10m	β^-	----------	----------	----------
34	Se 77	stable				
	Se 78	stable				
	Se 79	<10m or $>7\times10^5$y	β^-	----------	----------	----------
	Se 80	stable				
	Se 81*	59m	I.T., γ, e^-	0.008	e^-: 0.0868 (80%), 0.0964 (20%)	0.099
		57m			e^-: 0.085	0.098
	Se 81	17m	β^-	0.125	1.5	no γ
		19m				
	Se 82	stable				
	Se 83	25m	β^-, γ	0.21	1.5	0.17, 0.37, 1.1
		30m				
	Se 84	~2m	β^-	----------	----------	----------
35	Br 79	stable				
	Br 81	stable				
	Br 82	34h	β^-, γ	2.8×10^{-5}	0.465	0.547, 0.787, 1.35 1.0
	Br 83	2.4h	β^-	0.40	0.9	no γ
		2.45h		0.30	1.0	
		2.33h			1.3	
	Br 84	30m	β^-, γ	0.65	5.3	γ
		33m			4.5	
	Br 85	3.0m	β^-	----------	----------	----------
	Br 87	50s	β^-	----------	----------	----------
	Br (87)	55.6s	$\beta^-(n)$	----------	----------	----------
		56s				

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TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
36	Kr^{82}	stable		low		
	Kr^{83*}	113m	I.T., e^-	----	e^-: 0.032, 0.045, 0.028 e^-: 0.035	X-ray
	Kr^{83}	stable	----	----	----	----
	Kr^{84}	stable	----	----	----	----
	Kr^{85}	4.5h 4.6h 4.0h	β^-, γ	----	0.94 0.85	0.17, 0.37
	Kr^{85}	~10y	β^-	~0.24	0.74	no γ
	Kr^{86}	stable	----	----	----	----
	Kr^{87}	75m 74m	β^-	----	~4	----
	$Kr^{(87)}$	instantaneous	n	0.026% of fission neutrons	n: 0.30, 0.25	----
	Kr^{88}	3h 2.8h	β^-	----	2.5	----
	Kr^{89}	2.6m 2.5–3m 2–5m	β^-	----	----	----
	Kr^{90}	~33s	β^-	----	----	----
	Kr^{91}	9.8s 5.7s	β^-	----	----	----
	$Kr^{(92)}$	----	β^-	----	----	----
	$Kr^{(93)}$	2.0s	β^-	----	----	----
	$Kr^{(94)}$	1.4s	β^-	----	----	----
	Kr^{97}	short	β^-	----	----	----
37	Rb^{85}	stable				
	Rb^{86}	19.5d	β^-, γ	~1.6×10^{-4}	1.60 1.56	γ
	Rb^{87}	6.3×10^{10}y	β^-, γ, e^-	----	0.132, 0.13, 0.25	0.034, 0.053, 0.082, 0.102, 0.129
	Rb^{88}	17.8m 18m 17.5m	β^-	----	4.6 5.1	----
	Rb^{89}	15.4m 15.5m	β^-	----	3.8	----
	Rb^{90}	short	β^-	----	----	----
	Rb^{91}	short	β^-	----	----	----
	$Rb^{(92)}$	short	β^-	----	----	----
	$Rb^{(93)}$	short	β^-	----	----	----
	$Rb^{(94)}$	short	β^-	----	----	----
	Rb^{97}	short	β^-	----	----	----
	Rb	80s	β^-	----	----	----
38	Sr^{86}	stable		low		
	Sr^{87}	stable				
	Sr^{98}	stable				
	Sr^{89}	53d 54d 55d	β^-	4.6	1.50 1.52 1.5	no γ
	Sr^{90}	25y	β^-	----	0.6	no γ
	Sr^{91}	9.7h 10h 8.5h	β^-, γ	5.0	1.3 (40%), 3.2 (60%)	~1.3

TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
	$Sr^{(92)}$	2. 7h	β^-	5. 1	----------	----------
	$Sr^{(93)}$	7m	β^-	----------	----------	----------
	$Sr^{(94)}$	~2m	β^-	----------	----------	----------
	Sr^{97}	short	β^-	----------	----------	----------
39	Y^{89}	stable				
	Y^{90}	65h	β^-	----------	2. 2	no γ
		62h			2. 45	
		60h			2. 55, 2. 6	
	Y^{91}*	51m	I.T., γ, e^-	----------	e^-: ~0. 5	0. 61
		50m				(~10% converted)
	Y^{91}	57d	β^-	5. 9	1. 53, 1. 6, 1. 7	no γ
	$Y^{(92)}$	3. 5h	β^-, γ	----------	3. 4, 3. 6	0. 6, 0. 7–1. 1
	$Y^{(93)}$	10h	β^-, γ	----------	3. 1	0. 7
		11. 5h				
	$Y^{(94)}$	20m	β^-, γ	~5----------	----------	γ
	Y^{95}	<3h	β^-	----------	----------	----------
	Y^{97}	short	β^-	----------	----------	----------
40	Zr^{90}	stable				
	Zr^{91}	stable				
	Zr^{92}	stable				
	Zr^{93}	2. 5m	β^- (?)	----------	----------	----------
	Zr^{94}	stable				
	Zr^{95}	65d	β^-, γ	~6.4	0.394 (98%), 1.0 (2%)	0.73, 0.92 (?)
		65.5d				
		63d			~0.35 (98%), 1.0 (2%)	0.80
						0.88
					e^-: 0.71, 0.90 (?)	
	Zr^{96}	stable				
	Zr^{97}	17.0h	β^-, γ	----------	2.1	~0.8
41	Cb^{93}	stable				
	Cb^{95}*	90h	I. T., e^-,	----------	e^-: 0.22, 0.23	γ highly conv. (?)
		80h	X-ray		0.22	
						X-ray: ~0.016
	Cb^{95}	35d	β^-, γ	----------	0.15	0.75
		36.5d			0.15	0.77
						conv.
					e^-: 0.75, 0.77	0.79
						0.75
						~0.7
	Cb^{97}	75m	β^-, γ	----------	1.4	0.78
42	Mo^{95}	stable				
	Mo^{97}	stable				
	Mo^{98}	stable				
	Mo^{99}	67h	β^-, γ	6.2	1.2, 1.4	0.24, 0.75, 0.4
	Mo^{100}	stable				
	Mo^{101}	14.6m	β^-, γ	----------	1.0, 2.2	0.3, 0.9
		14m			1.9, 1.8	
	$Mo^{(102)}$	12m	β^-	----------	----------	----------
	Mo^{105}	short	β^-	----------	----------	----------

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TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
43	43^{99}*	5.9h	I. T., γ, e^-,	----------	e^-: 0.116	0.136
		6.6h	X-ray		0.12	0.129, ~0.18, X-ray
	43^{99}	4×10^6y		----------	0.3	----------
		~10^6y				
		~3×10^5y				
		>3000y				
		>40y				
	43^{101}	14.0m	β^-, γ	----------	1.3, 1.2 1 1	0.30
	$43^{(102)}$	<1m	β^-	----------	----------	----------
	43^{105}	short	β^-	----------	----------	----------
	$43^{(107)}$	<1.5m	β^-	----------	----------	----------
44	Ru^{99}	stable				
	Ru^{101}	stable				
	Ru^{102}	stable				
	Ru^{103}	42d	β^-, γ	3.7	0.2 (95%), 0.80 (5%)	0.56
		45d			0.2 (97%), 0.8 (3%)	0.54
	Ru^{104}	stable				
	Ru^{105}	4.5h	β^-, γ	~0.9	1.35	0.76
		4h			1.5	
	Ru^{106}	1.0y	β^-	0.48, 0.53	~0.03(?)	no γ
	$Ru^{(107)}$	4m	β^-	----------	~4	----------
45	Rh^{103}*	56m	I. T., e^-, X-ray	----------	e^-: ~0.03	X-ray: 0.020
		48m				
		45m				
	Rh^{103}	stable				
	Rh^{105}	36.5h	β^-, γ	----------	0.60	0.33
		34h			e^-: ~0.3	
	Rh^{106}	30s	β^-, γ	----------	~2.8 (20%), 3.9 (80%) ~4.5	0.3, 0.8 (low intensity)
	$Rh^{(107)}$	24m	β^-, γ (?)	----------	1.2	γ(?)
		26m				
	Rh^{109}	<1h	β^-	----------	----------	----------
	Rh	9h	β^-, γ	----------	~1.3	0.8
46	Pd^{105}	stable				
	Pd^{106}	stable				
	Pd^{107}	very short or >3×10^8y >8.6×10^7y	β^-	----------	----------	----------
	Pd^{108}	stable				
	Pd^{109}	13.4h	β^-	0.028(t)	1.1	no γ
		13.2h			1.03	
		13h				
	Pd^{110}	stable				
	Pd^{111}	26m	β^-	----------	3.5	----------
	Pd^{112}	21h	β^-	0.011	0.2	no γ

TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
47	Ag^{107}	stable				
	Ag^{109*}	40.4s	I. T., e^-, γ,	----------	e^-: 0.0664, 0.0896,	0.0426
		40s	Xray		0.0915	
						0.092
						0.09
	Ag^{109}	stable				
	Ag^{111}	7.6d	β^-, γ(?)	0.018(t)	~0.24(?), 1.0	no γ(?)
		7.5d			~0.8	γ (low intensity)
	Ag^{112}	3.2h	β^-, γ	----------	3.6, 2 2	0.86
48	Cd^{111}	stable				
	Cd^{112}	stable				
	Cd^{113}	stable				
	Cd^{114}	stable				
	Cd^{115}	2.33d	β^-, γ	0.011	~0.6, 1.13	0.65
		2.5d			1.11	0.55
					0.56 (60%), 1.20 (40%)	
	Cd^{115}	44d	β^-, γ(?)	0.0008	1.7	~0.5(?)
		43d			1.8	
		40d			1.5	
	Cd^{116}	stable				
	Cd^{117}	2.83h	β^-	0.01	1.3–1.7	----------
		2.72h				
	Cd^*	48.7m	I. T., e^-	----------	e^-: 0.17	----------
		50m				
49	In^{115*}	4.53h	I. T., γ, e^-	----------	e^-: 0.308, 0.332	0.338
		4.5h				
		4.1h			0.48	~0.4
	In^{115}	stable				
	In^{117}	1.95h	β^-	----------	1.73	no γ
		1.9h			1.90	
50	Sn^{117}	stable				
	Sn^{118}	stable				
	Sn^{119}	stable				
	Sn^{120}	stable				
	$Sn^{(121)}$	62h	β^-	0.014	0.76	no γ
		60h				
		~80h				
	$Sn^{(121,123)}$	130d	β^-	0.0012	1.44–1.53	no γ
	Sn^{122}	stable				
	$Sn^{(123)}$	10d	β^-, γ	0.0044	2.6	γ
		11d				
	Sn^{124}	stable				
	Sn^{125}	9m	β^-	----------	----------	----------
	Sn	~20m	β^-	----------	----------	----------
	$Sn^{(126)}$	β^-, γ(?)		0.1	(70m $Sn^{(126)}$ + ~60m $Sb^{(126)}$): 0.7 (60%), 2.7 (40%)	(70m $Sn^{(126)}$ + ~60m $Sb^{(126)}$): 1.2

TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
51	Sb^{121}	stable				
	Sb^{123}	stable				
	Sb^{125}	~2.7y	β^-,γ,X-ray	0.023 0.018	0.3(~65%), 0.7 (~35%) ~0.6	0.6 0.56 X-ray: 0.027
	$Sb^{(126)}$	~60m	β^-, γ(?)	----------	see 70m $Sn^{(126)}$	see 70m $Sn^{(126)}$
	Sb^{127}	93h 80h	β^-, γ	----------	1.15	0.72
	Sb^{129}	4.2h	β^-	----------	----------	----------
	$Sb^{(132)}$	~5m	β^-	----------	----------	----------
	Sb^{133}	<10m	β^-	----------	----------	----------
	$Sb^{(134)}$	<10m	β^-	----------	----------	----------
52	Te^{125}	stable				
	Te^{126}	stable				
	Te^{127}*	90d	I. T., e^-, X-ray	0.033	e^-: 0.055, 0.082, 0.085	X-ray: 0.028
	Te^{127}	9.3h	β^-	----------	0.70	no γ
	Te^{128}	stable				
	Te^{129}*	32d	I. T., e^-	0.19	e^-: 0.070, 0.10	X-ray
	Te^{129}	70m	β^-, γ, X-ray.	----------	1.8	0.3, 0.8
		72m			1.75 F. 1.7 1.6	 0.3, 0.7 X-ray: ~0.030
	Te^{130}	stable				
	Te^{131}*	30h 29h	I. T., e^-	~0.5	e^-: 0.147, 0.175	----------
	Te^{131}	25m 30m	β^-	----------	----------	----------
	$Te^{(132)}$	77h 66h	β^-, γ, e^-, X-ray	3.6	0.28 ~0.3, e^-	0.22 X-ray
	Te^{133}	60m	β^-	----------	----------	----------
	$Te^{(134)}$	43m	β^-	----------	----------	----------
	Te^{135}	>2m	β^-	----------	----------	----------
	Te	~1m	β^-	----------	----------	----------
53	I^{127}	stable				
	I^{129}	very long	β^-	----------	----------	----------
	I^{131}	8.0d 7.9d	β^-, γ, e^-	2.8(t)	0.595 0.60	0.367 0.080, 0.36, 0.4
	$I^{(132)}$	2.4h 2.3h	β^-, γ	----------	1.0 (~50%), 2.1 (~50%), 1.3	0.6 (~50%), 1.4 (~50%), 0.85
	I^{133}	22h 18.5h	β^-, γ	~4.5	1.3 1.1	0.55
	$I^{(134)}$	54m	β^-, γ	~5.7	----------	>1
	I^{135}	6.7h 6.6h	β^-, γ	5.6	1.35 1.5	1.6 1.3
	$I^{(136)}$	1.8m	β^-	----------	----------	----------
	I^{137}	30s	β^-	----------	----------	----------
	$I^{(137)}$	22.0s 23s	β^-, (n)	----------	----------	----------

TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
54	Xe^{129}	stable				
	Xe^{131}	stable				
	Xe^{132}	stable				
	Xe^{133}	5.3d	β^-, γ, e^-,		0.35	0.085, 0.083
		5.4d	X-ray		0.33, 0.32, 0.26	X-ray: 0.031, 0.040
					e^-:0.049	
	Xe^{134}	stable				
	Xe^{135*}	13m	I. T., γ, e^-		e^-: 0.50	0.54
		15.6m			A1; 0.6	
		10m				~0.5, 0.6
	Xe^{133}	9.2h	β^-, γ	5.9	0.94	0.25
		9.4h			0.96	0.26
		9.5h			0.92	
					0.90–1.0	
	Xe^{136}	stable				
	Xe^{137}	3.4m	β^-		~4	
		3.8m				
	$Xe^{(137)}$	instantaneous	n	0.17% of fiss. neutrons	n: 0.67	
					0.56	
	Xe^{138}	17m	β^-			
		16–18m				
	Xe^{139}	41s	β^-			
		~30s				
	Xe^{140}	16s	β^-			
		9.8s				
	Xe^{141}	3s	β^-			
		1.7s				
	Xe^{143}	1s	β^-			
	Xe^{144}	short	β^-			
	$Xe^{(145)}$	0.8s	β^-			
	Xe	68m	I. T. (?)			
55	Cs^{133}	stable				
	Cs^{135}	$>2.5\times10^4$y	β^-			
		$>2\times10^3$y				
	$Cs^{(136)}$	13d	β^-, γ	0.008, 0.011	~0.28	1.2
	Cs^{137}	33y	β^-, γ		0.5 (50%), 0.8 (50%)	0.75
					~0.4 (50%), 0.8 (50%)	0.7
	Cs^{139}	32m	β^-, γ		2.6	1.2
		33m				
	Cs^{139}	7m	β^-			
		10m				
	$Cs^{(140)}$	40s	β^-			
	Cs^{140}	short	β^-			
	Cs^{141}	short	β^-			
	$Cs^{(142)}$	~1–2m	β^-			
	Cs^{143}	short	β^-			
	Cs^{144}	short	β^-			
	$Cs^{(145)}$	short	β^-			
56	Ba^{135}	stable				
	Ba^{136}	stable		low		
	Ba^{137}	stable				
	Ba^{138}	stable				

TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
	Ba^{139}	85m 86m 87m	β^-, γ	6.3	2.2	0.6
	Ba^{140}	12.8d ~12.5d	β^-, γ, e^-	6.1 5.8	1.05 ~0.4 (25%), 1.0 (75%) 1 0 e^-: 0.50	0.542 0.529, 0.5
	Ba^{141}	18m	β^-, γ	4.6	----------	γ
	$Ba^{(142)}$	6m	β^-	----------	----------	----------
	Ba^{143}	>0.5m	β^-	----------	----------	----------
	Ba^{144}	short	β^-	----------	----------	----------
	$Ba^{(145)}$	short	β^-	----------	----------	----------
57	La^{139}	stable				
	La^{140}	40.0h 40.2h	β^-, γ	----------	0.90 (20%), 1.4 (70%), 2.12 (10%) 1.45, ~2.2 (low intensity) 1.41 1.5 1.75	0.335 (1%), 0.49 (7%), 0.83 (14%), 1.63 (74%), 2.3(4%) 0.335 (2%), 0.49 (5%), 0.87 (10%), 1.65 (77%), 2.3 (6%) 0.333, 0.505, 0.832, 1.61, 2.52. 1.69 (>97%), 2.5 (<3%) 2.0 2.1
	La^{141}	3.7h	β^-, γ(?)	----------	2.8	γ (?)
	$La^{(142)}$	74m 77m	β^-, γ	----------	----------	γ
	La^{143}	19m 20m ~15m	β^-	>4.3	----------	----------
	La^{144}	short	β^-	----------	----------	----------
	$La^{(145)}$	short	β^-	----------	----------	---------- ----------
58	Ce^{140}	stable				
	Ce^{141}	28d 30d	β^-, γ	5.7	0.55 0.65	0.21 0.22, 0.2,
	Ce^{142}	stable				
	Ce^{143}	33h 32h 36h	β^-, γ	5.4	1.35	0.5
	Ce^{144}	275d 300d	β^-	5.3	0.348 ~0.3	no γ
	$Ce^{(145)}$	1.8h	β^-	----------	----------	----------
	$Ce^{(146)}$	14.6m ~15m	β^-	----------	----------	----------
59	Pr^{141}	stable				
	Pr^{143}	13.8d 14d 14.2d 13.5d	β^-	----------	1.0 0.95	no γ
	Pr^{144}	17.5m 18m	β^-, γ, e^-	----------	3.07 3.0	0.135, 0.145(?)

TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
		17m			3.1	0.22, 1.25 (low intensity)
	Pr^{144}				3.2	
					2.8	
					e^-: 0.091, 0.128, 0.103(?)	
	$Pr^{(145)}$	4.5h	β^-	----------	3.1	no γ
		4.7h				
	$Pr^{(146)}$	24.6m	β^-, γ	---------- -----	~3	1.4
		25m				
60	Nd^{143}	stable				
	Nd^{144}	stable				
	Nd^{145}	stable				
	Nd^{146}	stable				
	Nd^{147}	11.0d	β^-, γ, e^-, X-ray	2.6	~0.4 (40%), 0.90 (60%)	0.58
					e^-: 0.03	X-ray: ~0.040
	Nd^{148}	stable				
	$Nd^{(149)}$	1.7h	β^-, γ or X-ray	----------	1.5	γ or X-ray
		2.0h				
	Nd^{150}	stable				
	$Nd^{(151)}$	short	β^-	----------	----------	----------
61	61^{147}	3.7y	β^-	----------	0.20	no γ
		4y				
		2.2y				
	61^{149}	47h	β^-, γ, X-ray(?)	1.4	1.1	0.25 (low intensity) X-ray(?)
	$61^{(151)}$	12m	β^-	----------	----------	----------
	61^{153}	$<$5m	β^-	----------	----------	----------
	61^{156}	$<$5m	β^-	----------	----------	----------
62	Sm^{147}	stable				
	Sm^{149}	stable				
	$Sm^{(151)}$	long	--------	----------	----------	----------
	Sm^{152}	stable				
	Sm^{153}	47h	β^-, γ I. T.(?)	0.15(t)	0.73	0.10, 0.57
					0.7	0.11, ~0.6 X-ray(?)
	Sm^{154}	stable				
	Sm^{155}	25m	β^-, γ	0.031	1.9	~0.3
		21m			1.8	
	Sm^{156}	~10h	β^-	~0.016	~0.8	----------
63	Eu^{151}	stable				
	Eu^{153}	stable				
	Eu^{155}	2y	β^-, γ	~0.03	~0.23	0.0844
	Eu^{156}	15.4d	β^-, γ	0.013	~0.5 (60%), 2.4 (40%)	2.0
	Eu^{157}	15.4h	β^-, γ	0.0074	~1.0 (75%), ~1.7 (25%)	0.2, 0.6
	$Eu^{(158)}$	60m	β^-	0.002	~2.6	----------
64	Gd^{155}	stable				
	Gd^{156}	stable				
	Gd^{157}	stable				
	Gd^{158}	stable				

TABLE I.—*Table of fission products: characteristics*—Continued

Nucleus Z	Nucleus A	Half-life	Decay	Fission yield, %	Energy of radiations in Mev: Particles	Energy of radiations in Mev: Gamma radiations
Unidentified fission product nuclei with daughters emitting neutrons instantaneously						
				% of fission neutrons		
(1)	4.51s 4.5s 3s		β^- (n)	0.21	n: 0.430	
(2)	1.52s 1.8s		β^- (n)	0.24	n: 0.620	
(3)	0.43s 0.4s		β^- (n)	0.084	n: 0.420	
(4)	0.05s		β^- (n)	~0.029		

Symbols:

β^-—Negative electrons emitted from the nucleus.

γ—Gamma rays.

e^-—Internal conversion electrons.

n—Neutrons.

I.T.—Isomeric transitions.

*—Nucleus in a metastable excited state, decaying by isomeric transition.

Where several values of the half-life or energy of radiation are given, they are those obtained by different investigators or by different experimental methods.

TABLE II.—*Table of fission products: chains and yields*

PART 1. LIGHT GROUP

Mass. No.	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Cb	42 Mo	43	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	Fission yield, %
71	•	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
72	49h→14.3h→stable		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	1.5×10^{-5}
73	<2m→5h→stable		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	1.0×10^{-4}
74	•	•	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
75	•	•	(89m)→stable		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
76	•	•	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
77	•	•	12h- - →40h→stable			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.0091
78	•	•	•	(80m)→stable		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
(78)	•	•	2.1h→90m→?			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.02
79	•	•	•	•	{<10m or >7×10^6y}→stable		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
80	•	•	•	•	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
81	•	•	•	•	59m	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.008
	•	•	•	<10m→17m→stable			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.125
82	•	•	•	•	stable	34th→stable		•	•	•	•	•	•	•	•	•	•	•	•	•	•	2.8×10^{-5}
83	•	•	•	•	25m→2.4h→113m		↓	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.40
	•	•	•	•	•	•	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
84	•	•	•	•	~2m→30m→stable			•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.65
85	•	•	•	•	•	3.0m→4.5h→stable			•	•	•	•	•	•	•	•	•	•	•	•	•	
	•	•	•	•	•	•	~10y		•	•	•	•	•	•	•	•	•	•	•	•	•	~0.24
86	•	•	•	•	•	•	stable	19.5d→stable		•	•	•	•	•	•	•	•	•	•	•	•	2×10^{-5} b
	•	•	•	•	•	55.6s→instant.d	↑	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.026c
(87)	•	•	•	•	•	•	?	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
87	•	•	•	•	•	50s→75m→6.3×10^{10}y→stable				•	•	•	•	•	•	•	•	•	•	•	•	
88	•	•	•	•	•	•	3h→17.8m→stable			•	•	•	•	•	•	•	•	•	•	•	•	
89	•	•	•	•	•	•	2.6m→15.4m→53d→stable				•	•	•	•	•	•	•	•	•	•	•	4.6
90	•	•	•	•	•	•	~33s→short→25y→65h→stable				•	•	•	•	•	•	•	•	•	•	•	
91	•	•	•	•	•	•	•	•	•	51m (~40%)	•	•	•	•	•	•	•	•	•	•	•	
	•	•	•	•	•	•	9.8s→short→9.7h→57d - →stable			↓	•	•	•	•	•	•	•	•	•	•	•	5.9
(92)	•	•	•	•	•	•	3s→short→2.7h→3.5h→stable				•	•	•	•	•	•	•	•	•	•	•	5.1
	•	•	•	•	•	•	•	80s→?		•	•	•	•	•	•	•	•	•	•	•	•	
(93)	•	•	•	•	•	•	2.0s→short→7m→10h→?→stable						•	•	•	•	•	•	•	•	•	
(94)	•	•	•	•	•	•	1.4s→short→~2m→20m→stable						•	•	•	•	•	•	•	•	•	~5
95	•	•	•	•	•	•	•	•	•	•	•	90h (~2%)	•	•	•	•	•	•	•	•	•	
	•	•	•	•	•	•	•	•	•	<1.5h→65d→35d→stable		↓	•	•	•	•	•	•	•	•	•	~6.4
96	•	•	•	•	•	•	•	•	•	•	stable	•	•	•	•	•	•	•	•	•	•	
97	•	•	•	•	•	•	short→short→short→short→17.0h→75m→stable							•	•	•	•	•	•	•	•	
98	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	•	•	•	•	•	•	
99	•	•	•	•	•	•	•	•	•	•	•	•	•	5.9h (~10%)	•	•	•	•	•	•	•	
	•	•	•	•	•	•	•	•	•	•	•	•	67h→4×10^5y→stable	↓	•	•	•	•	•	•	•	6.2
100	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	•	•	•	•	•	•	
101	•	•	•	•	•	•	•	•	•	•	•	•	14.6m→14.0m→stable			•	•	•	•	•	•	
(102)	•	•	•	•	•	•	•	•	•	•	•	•	12m→<1m→stable			•	•	•	•	•	•	

TABLE II.—*Table of fission products: chains and yields*—Continued

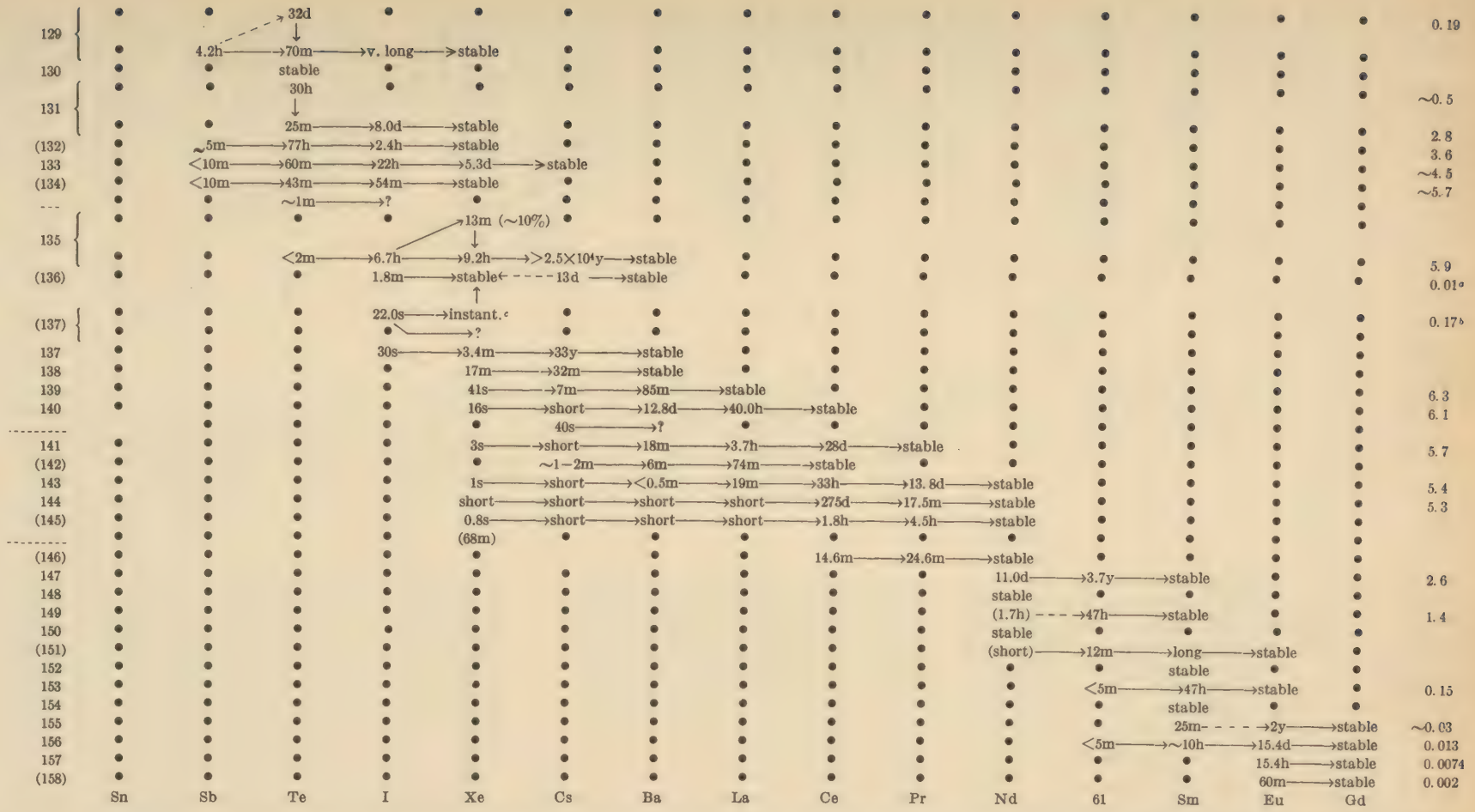
PART 1. LIGHT GROUP

Mass. No.	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Cb	42 Mo	43	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	Fission yield, %
103	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	56m (≥97%)	•	•	•	•	•	
	•	•	•	•	•	•	•	•	•	•	•	•	•	•	42d - - →	↓ stable	•	•	•	•	•	3.7
104	•	•	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	•	•	•	•	
105	•	•	•	•	•	•	•	•	•	•	•	•	short →	short →	4.5h →	36.5h →	stable	•	•	•	•	~0.9
106	•	•	•	•	•	•	•	•	•	•	•	•	•	•	1.0y →	30s →	stable	•	•	•	•	0.5
107	•	•	•	•	•	•	•	•	•	•	•	•	•	<1.5m →	4m →	24m - →	v. short or >3×10⁶y →	stable	•	•	•	
108	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	•	•	
109	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	(40.4s) ↓	•	•	•	
	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	<1h →	13.4h - →	stable	•	•	•	0.028
110	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	•	•	
111	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	26m →	7.6d →	stable	•	•	0.018
112	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	21h →	3.2h →	stable	•	•	0.011
113	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	
114	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	
115	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	2.33d →	4.53h ↓	•	0.011
	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	44d →	stable	•	0.0008
116	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	
117	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	2.83h →	1.95h →	stable	0.01
-------	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	48.7m ↓	•	•	
	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	stable	•	•	
	Zn	Ga	Ge	As	Se	Br	Kr	Rb	Sr	Y	Zr	Cb	Mo	43	Ru	Rh	Pd	Ag	Cd	In	Sn	

[a] Yield of 34h Br^{87} formed directly in fission; not representative of total chain yield. [b] Yield of 19.5d Rb^{86} formed directly in fission; not representative of total chain yield. [c] Delayed neutron yield based on fission neutrons rather than on fissions. [d] Instantaneous, *via* delayed neutrons.

PART 2. HEAVY GROUP

Mass No.	50 Sn	51 Sb	52 Te	53 I	54 Xe	55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61	62 Sm	63 Eu	64 Gd	Fission yield, %
118	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
119	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
120	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
(121)	62h →	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	0.014
(121, 123)	130d →	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	0.0012
122	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
(123)	10d →	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	0.0044
124	stable	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
125	(9m) →	~2.7y →	stable	•	•	•	•	•	•	•	•	•	•	•	•	0.023
(125)	~20m →	?	•	•	•	•	•	•	•	•	•	•	•	•	•	
(126)	70m →	60m →	stable	•	•	•	•	•	•	•	•	•	•	•	•	0.1
127	•	•	90d ↓	•	•	•	•	•	•	•	•	•	•	•	•	0.033
	•	93h →	9.3h →	stable	•	•	•	•	•	•	•	•	•	•	•	
128	•	•	stable	•	•	•	•	•	•	•	•	•	•	•	•	



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a Yield of 13d Cs (136) formed directly in fission; not representative of total chain yield. b Delayed neutron yield based on fission neutrons rather than on fissions. c Instantaneous, via delayed neutrons.

( )—Parentheses around mass number indicate the mass assignment is uncertain.

- - →—Broken arrow indicates the genetic relationship has not been definitely established.

SUBJECT INDEX

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